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THESIS

COMBAT SERVICE SUPPORT SOLDIER NETWORK ENABLED OPERATIONS (CSNEO)

by

Francisco R. Baez

June 2008

Thesis Advisor:	Susan M. Sanchez
Second Reader:	Jonathan Alt

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Modeling and simulation provides a cost effective means to gain insights into the potential benefits of network-enabled capabilities in a variety of operational settings. This research outlines a methodology and provides a use case for employing modeling and simulation in the identification of significant factors for network-enabled capabilities. The effort explores the use of the U.S. Army Training and Doctrine Command (TRADOC) Analysis Center's Logistics Battle Command (LBC) model to examine the distribution of capabilities across an organizational structure. It leverages large, space-filling designs of experiments, in conjunction with high performance computing clusters, to assess the impact of Soldier-level, network-enabled capabilities on transportation terminal node operations within a sustainment base supporting a Joint Force.

Further, this research coalesces experimental design and exploratory data analysis to examine 771 variants of the operational scenario. Three network structures are examined, namely, the Hierarchical, Star, and Hierarchical-Star topologies, to quantify the impacts of network-enabled capability on the velocity, reliability, and visibility measures of effectiveness. The results suggest that increasing network-enabled capabilities yields a significant return of investment over the current capabilities. The latter network topologies show that Soldiers performing terminal node cargo operations are better connected, and this leads to more responsive distribution systems.

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COMBAT SERVICE SUPPORT SOLDIER NETWORK ENABLED OPERATIONS (CSNEO)

Francisco R. Baez
Major, United States Army
B.S., University of Puerto Rico, 1996

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June 2008

Author: Francisco R. Baez

Approved by: Susan M. Sanchez
Thesis Advisor

Jonathan Alt
Second Reader

James N. Eagle
Chair, Department of Operations Research

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Modeling and simulation provides a cost effective means to gain insights into the potential benefits of network-enabled capabilities in a variety of operational settings. This research outlines a methodology and provides a use case for employing modeling and simulation in the identification of significant factors for network-enabled capabilities. The effort explores the use of the U.S. Army Training and Doctrine Command (TRADOC) Analysis Center's Logistics Battle Command (LBC) model to examine the distribution of capabilities across an organizational structure. It leverages large, space-filling designs of experiments, in conjunction with high performance computing clusters, to assess the impact of Soldier-level, network-enabled capabilities on transportation terminal node operations within a sustainment base supporting a Joint Force.

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EXECUTIVE SUMMARY

The United States Department of Defense (DoD) continues its transformation from industrial age military to one that is network-enabled. At the tactical level, distribution operations are about the delivery of supplies, personnel, and equipment from within the theater operations to point of need. Network-enabled and information systems provide the visibility of node and mode status in a shared Logistics Common Operating Picture (LCOP). Currently, there are a variety of communications systems employed that enable distribution operations; however, in some instances at the Soldier level these capabilities do not exist. Accordingly, individual units and commands have supplemented their units with a myriad of Commercial Off-The-Shelf (COTS) products as system and network enablers to fill current network enabled capability needs. Recognizing that a need exists to evaluate the CSS Soldier network enabled capabilities operations, the U.S. Army Training and Doctrine Command (TRADOC) Analysis Center in Monterey (TRAC-Monterey) is conducting the Individual Soldier Wireless Tactical Networking (ISWTN) Capability Based Assessment (CBA) to identify network enabled capability gaps for Combat Service Support (CSS) Soldiers and to identify potential solutions to fill those gaps.

This research explores the use of the Logistics Battle Command (LBC) model to assess the impact of Soldier level network enabled capabilities have on cargo operations at a truck terminal within a sustainment base supporting a JF. The LBC model, developed by TRAC-Monterey, is a low-resolution, object oriented, stochastic, and discrete event model that enables the analysis of sustainment battle command scenarios. The results from the simulation will provide operational insights to quantify the impacts of network enabled capability had the measures of effectiveness (MOE). Questions that will be answered in this research include:

- What network-enabled capability gaps exist in the execution of Transportation Soldiers terminal cargo operations tasks, under the identified conditions, to the identified performance standards?
- What distribution structures and types of network-enabled capabilities allow Transportation Soldiers to accomplish their task to specified standards under given conditions?
- Are the network-enabled capabilities currently available to individual Transportation Soldiers?

The analytical approach associated with this research focused on identifying the operational scenario, choosing input parameters, developing experimental designs tools to transform input data, apply those using modeling and simulation, estimate outcomes and MOE, and present the results. The three MOE of interest, Velocity, Reliability, and Visibility were derived directly from concept specific attributes listed in the Joint Logistics (Distribution) Joint Integrating Concept (JIC) in order to provide the linkage from the specific mission tasks to the estimated operational outcomes for each scenario. Similarly, the input parameters were derived from the Net-Centric Operational Environment JIC and subject matter knowledge obtained through focused interviews.

This study implements the Nearly Orthogonal Latin Hypercube (NOLH) experimental design technique, which provides a means to explore how changes in the input parameters or factors affect the simulation output. The factors in this experiment consist of In-Transit Visibility (ITV)-Available, ITV-Accuracy, LCOP-Update, probability of communications, latency, communication relay capability, resources available, convoys per hour, and convoy commodity case. The NOLH design qualities such as space filling, orthogonality, and flexibility allowed a thorough examination of the response surface for the given operational scenario.

The scenario used for this research focused on Army Transportation Soldiers performing cargo terminal operations at a Centralized Receiving and Shipping Point (CRSP) within a Forward Operating Base (FOB) in support of regular sustainment convoys delivering equipment, and supplies to their final destination. The Experimental design and exploratory data analysis allowed the experimentation of 771 design points to assess the impact of network enabled capability provided by three dissimilar network structures namely, Hierarchical, Star, and Hierarchical-Star topologies for the operational scenario.

- Velocity is affected by traffic intensity and ITV-Available, the most significant factors for all of the three network structures. Velocity improves as traffic intensity decreases. Setting ITV-Available to its highest value always results in better velocity.
- Overall, velocity improved by 32% and 42% with the Star and Hierarchical-Star network structures, respectively, in comparison to the Hierarchical network structure.
- Reliability is affected by traffic intensity and ITV-Available. Reliability improved with the Star and Hierarchical-Star network structures.
- The most significant factors influencing visibility differ by the network topology.
  - For the Hierarchical network structure, these are the communication relay capability at the supervisor lane, and the probability of communications between the supervisor and the LCOP.
  - For the Star network structure, these are the probability of communications between the LCOP and the pallet lane, as well as the LCOP and container lane, and the communications relay capability at the pallet lane.
  - For the Hierarchical-Star network structure, these are the communications relay capability at the supervisor lane, the probability of communications between the LCOP and the container lane, as well as the LCOP and pallet lane.
- Overall, visibility improved by 43% and 59% for the Star and Hierarchical-Star network structure, respectively, in comparison to the Hierarchical network structure.
- The Hierarchical network structure displayed limited ability to share situational understanding, and in the ability to access/share/exchange data information.
- The Star and the Hierarchical-Star network structures improve the level of visibility possessed by each of the element in the network.

Typically, architectural analysis based on subject matter expert input is the basis of the CBA process, and modeling and simulation is rarely used. However, the results from this research suggest that modeling and simulation combined with an efficient design of experiments will result in a more robust process and add credibility to the CBA findings.

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LIST OF ACRONYMS AND ABBREVIATIONS

AIT	Automated Information Technologies
ARCIC	Army Capabilities Integration Center
BCT	Brigade Combat Team
BSB	Brigade Support Battalion
BCS3	Battle Command Sustainment Support System
C2	Command and Control
CBA	Capabilities Based Assessment
CIO	Chief Information Officer
CJCSI	Chairman of the Joint Chief of Staff Instruction
CJCSM	Chairman of the Joint Chief of Staff Manual
CLP	Combat Logistic Patrol
CONUS	Continental United States
COP	Common Operating Picture
COTS	Commercial Off-The-Shelf
CRSP	Centralized Receiving and Shipping Point
CSS	Combat Service Support
DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, Facilities
FAA	Functional Area Analysis
FNA	Functional Needs Analysis
FOB	Forward Operating Base
FSA	Functional Solutions Analysis
FSC	Forward Support Company
HLS	National Strategy for Homeland Security
ISWTN	Individual Soldier Wireless Tactical Networking
ITV	In-Transit Visibility
JCIDS	Joint Capabilities Integration and Development System
JCS	Joint Chief of Staff
JDDE	Joint Deployment and Distribution Enterprise
JF	Joint Force
JFC	Joint Functional Concept
JIC	Joint Integrating Concept
JOC	Joint Operating Concept

JOpsC	Joint Operations Concepts
JOUN	Joint Urgent Operational Needs
JTRS	Joint Tactical Radio System
LCOP	Logistic Common Operational Picture
MHE	Material Handling Equipment
MOE	Measure of Effectiveness
MOUS	Mobile User Objective System
MTS	Movement Tracking System
NDS	National Defense Strategy
NMS	National Military Strategy
NSS	National Security Strategy
NCE	Net-Centric Environment
NCOE	Net-Centric Operational Environment
OIF	Operation Iraqi Freedom
PBUSE	Property Book Unit Supply-Enhanced
RFID	Radio Frequency Identification
SAAS-MOD	Standard Army Ammunition System-Modular
SAMS	Standard Army Maintenance System
SARSS	Standard Army Retail Supply System
SPG	Strategic Planning Guidance
STAMIS	Standard Army Management Information Systems
TAV	Total Asset Visibility
TC-AIMS	Transportation Coordinators - Automated Information for Movements System II
TRADOC	U.S. Army Training and Doctrine Command
TDC	Theater Distribution Center
ULLS	Unit Level Logistics System
WIN-T	Warfighter Information Network Tactical
WTN	Wireless Tactical Networking

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I. INTRODUCTION

A. BACKGROUND

Wireless Tactical Networking (WTN) supports mission critical voice, data, and video applications. WTN programs such as Joint Tactical Radio System (JTRS), the Mobile User Objective System (MUOS), and the Warfighter Information Network Tactical (WIN-T), which are central to the vision for communications transformation, require waveforms and protocols with features generally not available in Commercial Off-The-Shelf (COTS) products. Combat Service Support (CSS) Soldiers require affordable seamless tactical networking capability; certainly, this is true in fixed-base facilities, fixed-port facilities, sustainment bases, and forward operating bases (FOB). Because the current communications network does not support current force requirements, individual units and commands have supplemented their units with a myriad of COTS products as system and network enablers to fill current network-enabled capability needs. In fact, those capability needs or operational gaps demonstrate that the Joint Force (JF) needs a network-enabled capability that enables mounted and dismounted on-the-move communications, disseminates information at all levels of security, and extends the reach-back capabilities. Likewise, the JF is dependent upon a network-enabled capability to provide increased throughput for the movement or delivery of forces, along with sustainment from point of origin to points of need, with greater visibility, velocity, and reliability. Consequently, the JF requires a communications infrastructure that facilitates information sharing, collaboration, and situational awareness of all forces—from high-level headquarters at command centers, to an individual Soldier downtown tracking insurgents, to a CSS Soldier delivering supplies in a FOB, and to a civilian at a depot in search of a new supplier. Currently, Soldiers in Iraq and Afghanistan are enabling operations and successfully using commercial wireless technologies, sometimes procured in an ad hoc manner with operational, discretionary, and supplemental dollars, to augment or replace tactical networks, despite interoperability, security, and spectrum issues. For example, COTS equipment deployed in recent combat operations in support of Operation Iraqi Freedom (OIF), which supported over 200 command posts, used COTS IEEE 802.16 compliant radios to fill gaps where there was no fiber. According to the 2007 Individual Soldier Wireless Tactical Networking Study Project Coordination Sheet, several recent studies suggest that seamless integration of Individual Soldier-level wireless tactical networking devices prevalent in support operations areas requires a comprehensive independent analysis. These studies including the 2006 Network Enabled Battle Command and the 2007 Tactical Networks for Ground Forces, as well as anecdotal evidence obtained from Joint Urgent Operational Needs (JUON), integrated priority lists, and operational lessons collected.

Currently, forces in Iraq and Afghanistan are engaged in ways that could not be perfectly forecast; however, to prepare for that uncertain future it is paramount that the JF applies lessons learned from today's fight to future programs by determining what types of capabilities are required, and by turning those requirements to solutions in order to ensure success. Given the aforementioned facts, and recognizing that a need exists to evaluate the CSS Soldier network-enabled capabilities operations, the U.S. Army Training and Doctrine Command (TRADOC) Analysis Center in Monterey (TRAC-MTRY), in coordination with the Army Chief Information Officer/G-6 (CIO/G-6), is conducting the Individual Soldier Wireless Tactical Networking (ISWTN) Capability Based Assessment (CBA) using the Joint Capabilities Integration and Development System (JCIDS) analysis process. The overall objective of the CBA is to identify network-enabled capability gaps for CSS Soldiers and to identify potential solutions to fill those gaps (ISWTN CBA Functional Area Analysis, 2008).

The following paragraphs provide an overview of the JCIDS process with the intent to provide a general background and understanding of the particular approach to the problem used during the ISWTN CBA and this research.

1. Joint Capabilities Integration and Development System

The Chairman of the Joint Chief of Staff Instruction (CJCSI) 3170.01F (2007) defines JCIDS as a system responsible for "identifying, assessing, and prioritizing joint military capability needs" (p. 1). In general, the JCIDS analysis process ensures that validated capability gaps for achieving military effects are adequately addressed through changes in doctrine, organization, training, materiel, leadership development and education, personnel, and facilities (also known as DOTMLPF spectrum) to provide the required capabilities; therefore, increasing the JF effectiveness while reducing opportunities for adversaries. The JCIDS framework serves as the linkage from top-level strategies-to-concepts-to-capabilities and the production of tasks, conditions, and standards in order to provide a basis for identification of capability gaps and potential solutions, which is the purpose of the CBA process (TRAC JCIDS Code of Best Practice [COBP], 2005; Army Transportation Corps Functional Area Analysis, 2005). Discussed below in greater detail are the primary sources of strategy, joint concepts, and capabilities that form the basis for the JCIDS derived from the JCIDS governing documents, namely CJCSI 3170.01F (2007) and CJCSI 3170.01C (2007).

First, strategic guidance to include the National Security Strategy (NSS), the National Defense Strategy (NDS), the National Military Strategy (NMS), the National Strategy for Homeland Security (HLS), and the Strategic Planning Guidance (SPG) provides guidance at a high level on how to match warfighting means to national ends. Consequently, joint concepts refine the strategy, define the range of military operations from strategic to tactical, and frame the conditions under which tasks are performed in order to meet mission requirements. Joint conceptual foundations are resident within the Joint Operations Concepts (JOpsC) family, consisting of Joint Operating Concepts (JOCs), Joint Functional Concepts (JFCs), and Joint Integrating Concepts (JICs).

JOpsC describe how forces are expected to operate across the range of military operations, and so provide the operational context for transformation by linking strategic guidance with the integrated applications of the JF capabilities. Subordinate to the JOpsCs are the JOCs, which describe the operational ends or required effects of how the

JF will accomplish a strategic goal, and provide the essential capabilities from which to derive the JFCs. JFCs articulate how the future JF will perform a set of particular military functions across the full range of military operations to attain the required functional means, also known as required capabilities. The last of the joint concepts, the JICs, describe how a JF will perform its operations or functional capabilities in terms of essential tasks, attributes, and measures of effectiveness (MOE) and performance.

Throughout the course of literature review, several points of discussion became evident; essentially, the JCIDS prevalent use of the terms “capability”, “capability gaps,” “capability needs,” “required capability,” and “current/programmed capability.” Further discussion of these terms appears will facilitate the reader’s understanding of the JCIDS process and CBA methodology that are described later in this chapter. The first three definitions are taken directly from the CJCSI 3170.01F (2007), the remaining two are derived form the CJCSM 3170.01C (2007).

- *Capability* is “the ability to achieve a desired effect under specified standards and conditions through combinations of means and ways to perform a set of tasks” (CJCSI 3170.01F, 2007, p. GL-5).
- *Capability gap* is “the inability to achieve a desired effect under specified standards and conditions through combinations of means and ways to perform a set of tasks. The gap may be the result of no existing capability, lack of proficiency or sufficiency in existing capability, or the need to recapitalize an existing capability” (CJCSI 3170.01F, 2007, p. GL-5).
- *Capability needs* is “a capability identified through the Functional Area Analysis (FAA) required to be able to perform a task within specified conditions to a required level of performance” (CJCSI 3170.01F, 2007, p. GL-5).
- *Required capability* is an FAA output and consists of a task, derived from a concept that must be performed to standard under a given set of conditions to achieve a desired effect or military objective. Whether the task can actually be performed or not is immaterial in the use of the term required capability (CJCSM 3170.01C, 2007)
- *Current/programmed capabilities* are the developed and fielded DOTMLPF solutions that have already made it to the force and those that are already planned or programmed to enter the force designed to achieve a specific effect through performance of a set of tasks to specified standards under specified conditions (CJCSM 3170C, 2007).

Although there are many joint required capabilities, the different services (e.g., Army, Navy, Air Force, and Marine Corps) deal with their own set of circumstances and operational challenges. Because of this, the different services synchronize their concepts with those of the joint community to more clearly define their complementary and reinforcing effects, based on their unique required capabilities, in order to achieve the mission requirement of the JF. The result is a set of essential (i.e., required) warfighting capabilities described in relevant operational terms that enables the JF to achieve mission requirements and strategic goals (TRADOC Pamphlet 525-66, 2005).

Once clearly defined goals or sets of required capabilities are identified, JCIDS through the CBA methodology is intended to develop integrated joint capabilities that reflect a common understanding of existing JF operations and of DOTMLPF capability gaps. According to CJCSM 3170.01C (2007), the CBA "is the analysis part of the JCIDS process that defines capability needs, capability gaps, capability excesses and approaches to provide those capabilities within a specified functional or operational area" (p. A-1). The Joint Chief of Staff (JCS) J-8 CBA User's Guide (2006) and the most recent Army Capabilities Integration Center (ARCIC) CBA Guide (2008) describe the CBA process as a structured, three-phased JCIDS analyses methodology which defines required capabilities, capability gaps, capability needs, and approaches to provide those capabilities, within a specified functional or operational concept. The three major steps of the CBA are the Functional Area Analysis (FAA), the Functional Needs Analysis (FNA), and the Functional Solution Analysis (FSA). Described below is a summary overview of these steps adapted from the JCS J-8 CBA User's Guide (2006) and the ARCIC CBA Guide (2008).

The FAA is the first analytical step of the CBA. It uses an approved JOC, JFC, or JIC, in addition to service concepts to identify the specific operational tasks (i.e., the current and potential capabilities) required to achieve military objectives, the conditions (i.e., the variables of the environment that affect the performance of a task) under which the force must accomplish those tasks, and the standards (i.e., the measures and criteria of performance) that must be met to accomplish those tasks. The result is a set of tasks that the JF needs to perform to standard under the specified conditions mapped to each required capability. This tasks, conditions, and standards set constitute the JF required capabilities and serve as input to the follow-on FNA phase.

The FNA, at times referred to as a capability gap analysis, is the second step in the CBA. It is a comparison of current and programmed capabilities with the capabilities needed to perform tasks and missions, under operating conditions, and to the prescribed standards. Scenarios and concepts are applied to give context to the tasks and missions. If the existing or programmed capabilities do not allow accomplishment of a task or mission to the determined standard under a defined set of conditions, then a capability gap exists. In other words, those required capabilities, identified during the FAA, that cannot be performed or that are inadequately performed with existing and programmed resources are defined as capability gaps. These capability gaps are then prioritized, based on an assessment of the likelihood of occurrence and impact on operational success. The output of the FNA is a set of capability gaps, sometimes referred to as potential investment opportunities. Similarly, the FNA produces a set of capability redundancy that reflects areas where inefficient and excess capacity exists to accomplish the required capabilities, sometimes referred to as potential divestiture or trade-space opportunities. These identified sets of capability gaps and redundancies are the inputs to the FSA.

The FSA is the third step in the CBA. It uses an operationally-based assessment to examine the prioritized list of capability gaps from the FNA to determine potential DOTMLPF solutions to achieve gap closure in an operational context, and assesses the operational risk of not filling identified gaps. The output of the FSA is a prioritized list of approaches for overcoming the identified gap which influences the future direction of integrated architectures and provides input to capability portfolios.

B. THE OPERATIONAL PROBLEM

Several joint and service concepts, logistics studies and analyses, as well as government sponsored studies, recognize that the current distribution system is characterized by deficiencies in three areas: In-Transit Visibility (ITV), networked communications, and information systems that provide network-wide visibility of node and mode status in a shared Logistics Common Operating Picture (LCOP). These deficiencies jeopardize the ability to build a sustainment system that ensures the right supplies and services will arrive on time and at the desired location.

C. PURPOSE

This research uses modeling and simulation efforts and experimental design techniques to provide quantitative data for assessing the impact that Soldier-level network-enabled capabilities have on cargo operations at a truck terminal within a sustainment base supporting a JF as part of the FNA process of the ISWTN CBA. In addition, this research will provide operational insights for identifying capability gaps in performance, and determining the operational impact each gap has on the MOE. A secondary purpose for this research is to determine whether simulation results support those obtained from other ISWTN CBA FNA tools.

D. SCOPE

This research focuses on Army Transportation Soldiers performing terminal operations within a sustainment base. This study concentrates on the current force capabilities and attributes, rather than specific systems, using an operational scenario to provide the operational context for the qualitative analysis conducted by TRAC-MTRY as part of the ISWTN CBA. This research follows the JCIDS guidance in both the input and the output of this effort. The capabilities, tasks, and MOEs are derived directly from published joint concepts and FAA. The capability gap analysis is performed in the context of a scenario based on current sustainment base operations using data acquired from unclassified sources. Although the scenario used in this research is simulating sustainment operations, the results of the analysis will be used to identify more inclusive network enabled capability gaps.

E. RESEARCH QUESTIONS

The following specific research questions scope the direction of the research:

- What network-enabled capability gaps exist in the execution of Transportation Soldiers terminal cargo operations tasks, under the identified conditions, to the identified performance standards?
- What distribution structures and types of network-enabled capabilities allow Transportation Soldiers to accomplish their task to specified standards under given conditions?
- Are the network-enabled capabilities currently available to individual Transportation Soldiers?

F. SIGNIFICANCE

This effort is vastly significant because of its timely relevance and scope. The question of which network-enabled capability gaps exist is arguably one of the most important questions for the overall ISWTN CBA. The results from this effort will support the qualitative analysis findings from the FNA phase of the ISWTN CBA. The resulting recommendations from this research may serve to validate the identification of required capabilities, as well as identify essential issues that should be considered during the capability gaps prioritization process; therefore, this research fosters the process that shapes future capabilities. Above all, CSS Soldiers who may be operating from a fixed-based facility in the theater of operations will benefit from the potential solutions to those capability gaps.

G. THESIS OVERVIEW

This brief introductory chapter is followed, in Chapter II, with a discussion of literature review results and the background information that supports the study. Chapter III provides a description of the operational scenario and an overview and description of the Logistics Battle Command (LBC) model. Chapter IV covers the measures of effectiveness and design of experiments used to facilitate the execution of the model. Chapter V details the analysis completed on the model output data. Chapter VI provides conclusions and future research recommendations.

II. LITERATURE REVIEW

This chapter provides a general overview of the current joint distribution operations and the role that transportation operations play within distribution operations in the joint context. The next section describes the Centralized Receiving and Shipping Point (CRSP) concept, its organization, and typical operations. The intent of this chapter is to provide background information mainly for readers who are not familiar with current state of distribution systems, Army Transportation operations, and the CRSP concept, which are the focus and foundation for the scenario developed for this research.

A. JOINT DISTRIBUTION OPERATIONS

According to JP 4-01.4, Joint Tactics, Techniques, and Procedures for Joint Theater Distribution (2000), distribution is “the operational process of synchronizing all elements of the logistics system to deliver the right things to the right place at the right time, to support the combatant commander” (p. I-1). In addition, it defines the distribution pipeline as “the end-to-end flow of resources from supplier to point of consumption, and in some cases back to the supplier in retrograde activities” (p. I-1). In broad terms, joint distribution operations provide for the multi-directional flow of personnel, equipment, materiel, and units from origin to point of employment or consumption with velocity, precision, accuracy, visibility, and centralized management. Joint distribution is discussed in the 2006 Joint Logistics (Distribution) JIC (JL (D) JIC). This concept calls for a joint deployment and distribution enterprise (JDDE) capable of providing prospective JF commanders with the ability to rapidly and effectively move and sustain joint forces to support the full spectrum of operations. It emphasizes that distribution must be managed as a seamless process at the strategic, operational, and tactical levels; also, that these levels must be connected by a robust communications capability that allows for the ability to monitor and manage distribution in near real-time to affect and see what is in the network at all times (JL (D) JIC, 2006). This asserts that the establishment of a net-centric capability, according to the 2003 Net-Centric Environment JFC (NCE JFC) and the 2006 Net-Centric Operational Environment JIC

(NCOE JIC), enables the JF to improve the entire distribution pipeline. In fact, NCOE capabilities impact the distribution operations by providing the technical and knowledge capabilities that enable the connectivity and decision making.

The distribution pipeline is composed of two segments, strategic and theater. The strategic segment entails moving assets from their point of origin to a port of embarkation, and then on to a port of debarkation in a theater of operations. The theater segment begins at the theater port of debarkation and extends to the final destinations or points of need within the theater of operations. The theater distribution system is the compilation of the physical, financial, information, and communication networks (JP 4-01.4, 2000). Discussed below are certain aspects of these networks; specifically, the information and communication networks. The physical and financial networks are beyond the scope of this research.

The physical network is composed of all the physical facilities, structures, and resources used to physically store, maintain, move, and control the flow of assets between the point of issue to using activities and units; this flow includes retrograde activities (JP 4-01.4, 2000).

The financial network "consists of the policies, processes, and decision systems that obtain, allocate, and apportion the fiscal resources necessary to acquire and maintain distribution capabilities, and execute the distribution missions" (JP 4-01.4, 2000, p. I-8).

The information network is "the synergistic combination of all data collection devices, automatic identification technologies (AIT), automated data and business systems, decision support tools, and asset visibility capabilities supporting or facilitating theater distribution" (JP 4-01.4, 2000, p. I-8). There are a variety of systems used by joint and service organizations involved in theater segment, though many are organization centric and do not communicate or transfer data readily. The Army currently uses a host of Standard Army Management Information Systems (STAMIS) in the theater distribution segment, such as Standard Army Retail Supply System (SARSS), Unit Level Logistics System (ULLS), Standard Army Maintenance System (SAMS), Standard Army Ammunition System-Modular (SAAS-MOD), and Property Book Unit

Supply-Enhanced (PBUSE) System. In addition, there are a plethora of function-specific systems that are used to manage and monitor specific commodities. The majority of these transactional systems were developed to meet specific functional requirements by individual organizations. There are, however, systems that have wide application and have improved logistics information management, such as the Transportation Coordinators - Automated Information for Movements System II (TC-AIMS), the Movement Tracking System (MTS), and Radio-Frequency Identification (RFID) tags; the Battle Command Sustainment Support System (BCS3), which mines data from STAMIS to develop a LCOP, is another system with wide application (Concept Capability Plan for Distribution Operations for the Modular Force, 2007).

The communications network, which carries the data of the information network, serves as the link for the physical, financial, and information networks of the distribution system (JP 4-01.4, 2000). There are a variety of communications systems employed in the theater of operations to support the force. While there are a number of separate and linked nets, there is no single network that provides guaranteed communications for all organizations. Current theater communications are borne on Combat Service Support Automated Information Systems Interface (CAISI) and Very Small Aperture Terminal systems (VSAT). CAISI is a wireless frequency, line-of-sight, last mile/front-line data and voice communications hardware solution. VSAT is the SATellite COMmunications (SATCOM) dish antenna hardware that provides automated systems users access to global satellite data and voice communications. CAISI and VSAT communications capability currently serve existing STAMIS by providing assured communications (Combined Arms Support Command [CASCOM] Digital Command and Control (C2)/LCOP Training Support Package, 2006).

1. Asset Visibility

JP 4-01.4 (2000) defines Total Asset Visibility (TAV) as “the ability to see materiel across the distribution continuum” (p. V-3). In general, TAV is a technical capability that accesses existing data in current STAMIS to provide the status of asset production, repair, fielding, requisition, and stockage levels.

On the other hand, ITV is a subset of TAV. ITV is the capability designed to provide the customer with maximum visibility and near real-time status on the movement of cargo, passengers, medical patients, and personal property from source of supply to user. The primary function of ITV is to use existing STAMIS to provide real-time visibility of material that is specifically in-transit. ITV is used to monitor and redirect (if necessary) the movement of equipment and supplies to allow the prioritizing of logistics operations. ITV is the in motion/movement tracking portion of TAV (JP 4-01.4, 2000). One of the major sources of ITV data transmitted is AIT information generated in the STAMIS and passed through the ITV server network.

AIT is a family of read-and-write data-storage technologies that provide rapid and accurate acquisition, retention, and retrieval of source data. AIT includes such media types as bar codes, optical memory cards, RFID tags, and satellite-tracking systems to track materiel that is in transit. These devices and systems capture information electronically and pass it to the STAMIS and various distribution-related automated information systems. Several studies and lessons learned certify that when used correctly, AIT reduces the lengthy and error-prone manual component of conventional data entry, improves accuracy, increases the speed of logistics processes, and provides precise asset visibility throughout the distribution pipeline (CASCOM Digital C2/LCOP Training Support Package, 2006).

RFID tags are a data collection and storage device designed to provide stand-off visibility of container and pallet contents, and ITV of critical assets moving through the distribution network. Fixed or handheld RF interrogators read, when queried, these RFID tags automatically at aerial and sea ports of embarkation and debarkation, and at transportation nodes, terminal nodes, and sustainment bases. These RF technologies allow automatic identification and tracking of assets as they move through the distribution network. Information collected throughout the distribution network is immediately available through a business process server at each facility and through ITV servers located in both Continental United States (CONUS) and Outside the Continental United States (OCONUS) facilities. The ITV server provides a mechanism for users to query shipment status and location information; it also feeds data to TAV servers (CASCOM Digital C2/LCOP Training Support Package, 2006).

2. Logistics Common Operating Picture

JP 3-0, Joint Operations (2006), defines Common Operating Picture (COP) as "a single identical display of relevant information shared by more than one command. A COP facilitates collaborative planning and assists all echelons to achieve situational awareness." Hence a COP is an operational picture tailored to the user's requirements based on common data and information shared by more than one command.

During OIF, the Combined Forces Land Component Command (CFLCC) defined LCOP as: "a graphical decision aid which allows the CFLCC Commander and Staff to rapidly assess the logistical readiness of the command and identify problems. The LCOP must ultimately present a current picture and a predicted picture, focusing on force-tracking, force-closure, readiness, and distribution management, in order to allow timely decision-making" (Spencer, 2003). Thus, the LCOP, like the COP, is a single display of relevant information within a commander's logistics arena. Further, the LCOP is a distributed data processing and exchange environment for developing a dynamic database of objects, allowing each user to filter and contribute to this database according to the user's area of responsibility and command role (CASCOM Digital C2l/LCOP Training Support Package, 2006).

B. U.S. ARMY TRANSPORTATION OPERATIONS

Army transportation operations include planning, coordinating, and executing tasks to employ transportation resources providing the capabilities needed to allow the JF to achieve the operational ends. These operations include movement control, mode operations, and terminal operations. Movement control is the planning, routing, scheduling, controlling, coordination, and ITV of personnel, units, equipment, and supplies moving over lines of communication. It involves synchronizing and integrating logistics efforts with other elements span the spectrum of military operations. Mode operations include movement of personnel, cargo and equipment via intra-theater air, local and line-haul motor transport, heavy equipment transport, rail, coastal and inland waterway transport. A terminal operation is the staging, loading, discharge, transfer handling and documentation of cargo and manifesting of personnel among various transport modes (FM 4-0, 2003; FM 4-01.30, 2003).

The U.S. Army Transportation Corps FAA (2005) states that Army transportation organizations form the core for the theater distribution network for its operational capabilities that no other service possesses. In particular, Army movement control operations provide key elements of Joint C2, Battlefield Awareness, and Protection that enable the JF Commander with to see, understand, and act. Further, Army mode and terminal operations comprise the JF's most significant source of user land transportation and port operations.

C. CENTRALIZED RECEIVING AND SHIPPING POINT CONCEPT

1. Overview

A Centralized Receiving and Shipping Point (CRSP) is a terminal node of the theater distribution system. It is a dock-to-dock distribution center, open warehouse facility, within an area of operations (AO) where cargo is delivered, sorted, shipped, and backhaul cargo (also referred to as retrograde cargo) is picked up 24/7. The objective is to continuously move cargo quickly and efficiently using regular sustainment deliveries from theater to a CRSP, FOBs, or other CRSPs in the Brigade Combat Teams (BCT) AO. In terms of the familiar "hub and spoke" distribution concept, CRSPs are the "hubs" moving cargo to and from several supported FOBs being the "spokes." Similarly, the CRSP arranges for backhaul of cargo from regional hubs to theater. CRSPs in current operations act as the transfer point for cargo that includes all supplies, except ammunition. The cargo consist mostly of containers, pallets, flat racks, deploying and redeploying unit vehicles, and unserviceable or battle damaged unit equipment. In short, the CRSP concept is a fluid flow of trucks and commodities that are received from theater and delivered to customers; ideally, CRSP operations maximize vehicle loads, minimize trans-loading time, minimize the time spent at the CRSP, and reduce the number of convoys and combat logistics patrols (CLP) moving in the AO (CRSP Handbook, 2007; Lajoie, 2007).

2. CRSP Concept of Operations

Under the CRSP concept of operations, depicted in Figure 1, shipments coming from CONUS that arrive at the supported theater Aerial Ports of Debarkation (APOD) and Sea Ports of Debarkation (SPOD) are routed to the theater base, known as the Theater Distribution Center (TDC) CRSP. From here they are routed to other regional hubs such as CRSPs, or FOBs. The TDC CRSP receives multiple consignee shipments, configures these into single consignee shipments, and pushes the cargo to the appropriate satellite nodes using theater transportation assets or intra-theater and strategic air assets. Once theater transportation assets conducting line-haul operations between common-user terminals arrive at a CRSP, they are unloaded and reloaded with retrograde items that are scheduled for return to the TDC CRSP. Cargo arriving at the CRSPs either by air (e.g., theater aircraft assets, or cargo and utility helicopters) or ground is throughput to Brigade Support Battalions (BSB) or other CRSPs for distribution within the AO; this occurs using local-haul truck assets in a “race track” manner to maintain a continuous flow of sustainment and retrograde items. Cargo is then throughput to maneuver units or other organizations within the AO. Air sorties flown by the Air Force theater airlift organization in the AO may also deliver supplies into CRSPs and units operating at this level of war (CRSP Handbook, 2007).

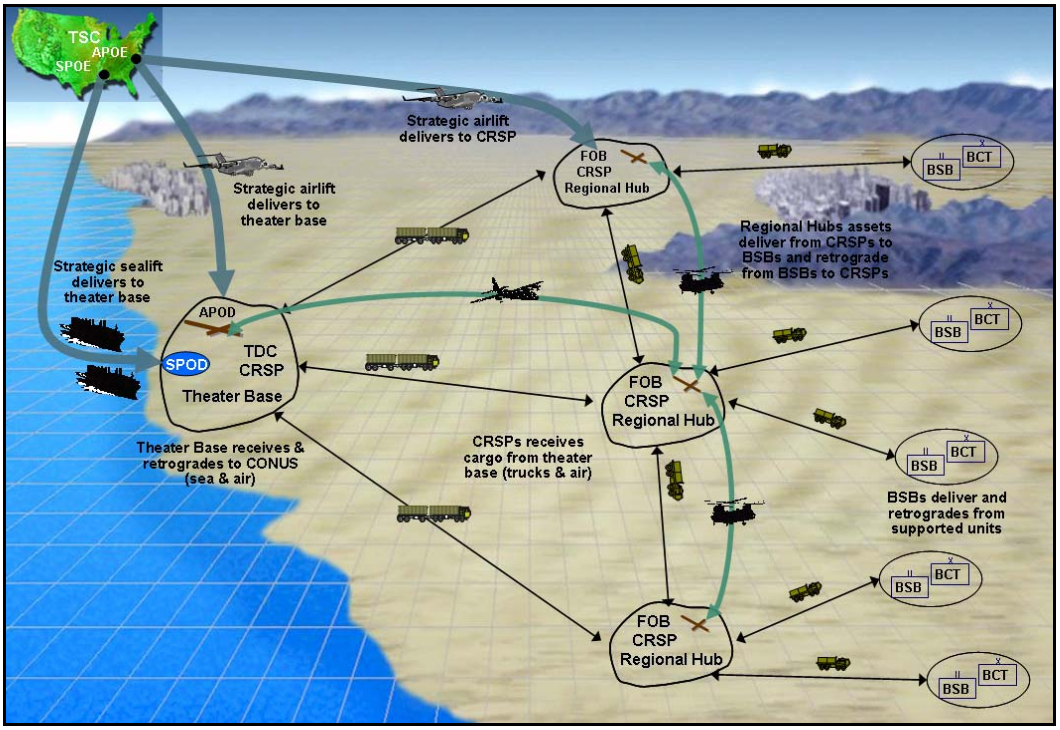

Figure 1. CRSP Concept of Operations (After CRSP Handbook 2007 and U.S. Concept Capability Plan for Distribution Operations, 2007)

3. CRSP Layout

CRSPs (in current operations) are different in size with different layouts. Nevertheless, most of the CRSPs are composed of an operations center, a palletized cargo area, customer container area/lanes, Class VII (e.g., unit vehicles) or rolling stock area/lanes, a battle damaged vehicle area, and an empty container collection point (ECCP) area to ensure fluid vehicle movement within the CRSP yard. Figure 2 is a proposed layout of a CRSP taken directly from the article *Using Central Receiving and Shipping Points to Manage Transportation* which appeared in the *Army Logistician* magazine (Melendez, 2007).

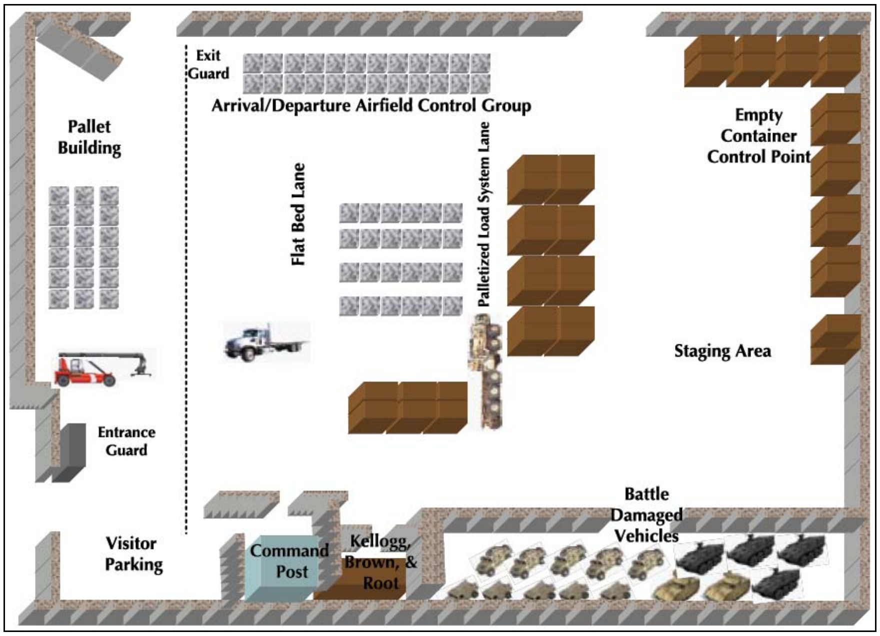

Figure 2. Proposed CRSP Layout (From Melendez, 2007)

Typically, an inbound and an outbound lane comprise the customer container area. Containers that have completed the final leg of their movement or are to be picked up at the CRPS are staged in the inbound container lane. Containers that will continue their onward movement are staged in the outbound container lane. Class VII or rolling stock is usually treated in the same manner as containers, with the exception that the rolling stock lanes require a much larger area. A palletized cargo area allows for pallets to be built and convoys to come in and stage so that one side offloads and the other side uploads. The battle damaged vehicle area segregates these vehicles from other retrograde cargo for preparation to be retrograded to theater. ECCPs are established for cross loading containers used for retrograde cargo arriving from the FOBs and to exchange any carrier-owned and leased-owned containers with government-owned containers. Finally, the operations center is the central location where all of the cargo entering and exiting the yard is processed and accounted for; additionally, the operations center synchronizes the CRSP efforts and priorities of each lane and sections to ensure uninterrupted operations (CRSP Handbook, 2007; Lajoie, 2007).

4. Inland Cargo Transfer Company

The CRSP Handbook (2007) proposes the personnel required and their responsibilities for a CRSP. A literature search and subject matter expert (SME) input reveals that the Cargo Transfer Company (CTC) has been the most efficient and suitable unit to operate a CRSP since the establishment of the first CRSP in Iraq in December 2004 (Lajoie, 2007; Melendez, 2007). However, in 2007 the CTC Modified Table of Organization and Equipment (MTOE) changed, focusing CTC operations to conduct inland terminal operations.

The Inland Cargo Transfer Company's (ICTC) defined mission is to discharge, load and transship cargo at air, rail or truck terminals; to supplement cargo/supply handling operations to alleviate cargo backlogs; and to operate the cargo marshalling area as required. The ICTC is composed of one operations section, one maintenance section, one documentations section, two cargo transfer platoons, and one headquarters platoon. The ICTC include Soldiers with three military occupational specialties (MOS): 88M, 88H, and 88N (ICTC MTOE, 2008).

First, the 88Ms are the motor transport operators. They are the heavy vehicle drivers capable of operating nearly every vehicle or rolling stock entering the CRSP during loading and unloading procedures. Next, the 88Hs are the cargo specialists. They are the cargo checkers and handlers and are required to operate all of the CRSP's Materiel Handling Equipment (MHE) to load and unload cargo such as forklifts, container handlers, and cranes. Last, the 88Ns are the transportation management coordinators. They are responsible for the operational functions of the CRSP. The 88Ns are accountable for the cargo in the yard; they ensure that convoys are loaded with the appropriate shipments and that the proper documentation is accurate and made available to convoy commanders (Lajoie, 2007; ICTC MTOE, 2008).

5. Typical CRSP Operations

When a convoy arrives to load or unload cargo, it is escorted to a staging area. After the convoy is staged, the convoy commander reports to the operations center with the documentation and manifest for the loads. A load/download team is assigned to receive or download the cargo and direct it, based on the documentation, to designated areas or lanes. As cargo is loaded or downloaded, an inventory is conducted based on the documentation, manifest, and RF tag information. Some of the essential information gathered during this inventory includes pertinent information about the convoy, cargo type, model, serial number, container size, container number, and RF tag number. Any unidentifiable cargo is identified as frustrated cargo. Explicitly, frustrated cargo is stopped at the CRSP because further disposition instructions must be obtained; this increases the cargo processing time, thus delaying the delivery of parts and materials to units. Once the cargo is received or loaded and the convoy is staged for departure, the load/download team provides the convoy commander with the proper documentation representing the transfer of custody of the cargo from the convoy commander to the CRSP for inbound cargo and vice versa for outbound cargo. All of the information gathered is imported into a web based information database that all stakeholders can access to maintain awareness and ITV of the cargo as it moves through the distribution system (Lajoie, 2007; Melendez, 2007).

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III. SCENARIO AND LOGISTICS BATTLE COMMAND MODEL

This chapter provides an overview of the scenario used as the basis for the analysis. This will provide readers with an understanding of why the scenario was chosen to evaluate the impact of network-enabled capabilities. The next section describes the LBC simulation software, followed by the research's constraints, limitations, and assumptions.

A. THE SCENARIO

As discussed in the introductory chapter, the purpose of this research is to use a modeling and simulation approach to examine current sustainment operations. The base case scenario selected for this research resulted from an extensive literature review, as well as SME input obtained through focused interviews completed during the FAA phase of the ISWTN CBA. Results from both provided the scope and the context to the analysis necessary to evaluate network-enabled capabilities in an operational environment.

1. Vignette Conditions at the Tactical Level

Military operations are currently in progress across the Joint Operations Area (JOA). Divisions and brigades are deployed to their operating locations and engaged with the enemy. Joint forces are now integrated into both operational and logistics plans, where they and contribute capability to and call on support from other coalition forces. Joint forces have established the theater base and distribution network to include the theater ITV and asset visibility network to monitor and track resources in order to support decisive operations. The logistics brigade operating the arterial theater distribution network has stocked the regional hubs and is able to support the logistics brigades providing area support to the formations by conducting daily CLP. Support battalions in the logistics brigades have established small supply support activities in order to quickly respond to requests from the BCTs. Retrograde missions are now occurring regularly, using the distribution network in reverse. Operating as part of the JF, Army Transportation units are conducting mode, terminal, and movement control functions in support of the theater distribution system.

2. Concept of the Operations

Transportation ICTC unit Soldiers conducting terminal cargo operations will conduct typical CRSP operations in support of regular sustainment operations. ICTC unit Soldiers operate the container lane, pallet lane, rolling stock lane, and the operations center in the CRSP. Regular sustainment operations include CLPs composed of thirty trucks with different commodities (e.g., containers, pallets, and rolling stock items), conducting line-haul operations at the tactical level to deliver personnel, equipment, and supplies to their final destination using the CRSP concept of operations (Chapter II Section D). Theater assets conduct line-haul operations between common-user terminals while local-haul truck assets provide final distribution of supplies and equipment to BCTs.

3. Network Structures Explored

The scenario built for this study is designed to assess three network structures and the ability to accomplish the mission in the assigned scenario. Incorporating network-enabled capabilities in the scenario involves connecting various lanes as nodes in the communications network. The three network structures implemented in LBC for this study are the Hierarchical, Star, and Hierarchical-Star network structures.

The Hierarchical network structure represents the current and programmed physical laydown and connectivity for the current force. Specifically, operations in the CRSP are largely governed by paper-based manifests, radio reports, and RF technology capability. The CRSP operations center can access the LCOP and develop detailed plans based on the ITV data, but those plans are made available to the container, pallet, and rolling stock lane in ad hoc manner by radio, face-to-face, and paper message processes.

These ad hoc methods are time consuming and operationally non-responsive. In contrast, the Star and Hierarchical-Star structures are two dissimilar topologies that represent increased network-enabled capabilities compared to the Hierarchical case.

a. Hierarchical Network Structure

The Hierarchical network structure, outlined in Figure 3, represents a topology that outlines the interconnection of five network-enabled nodes through four communication channels in a hierarchical manner. The LCOP node is at the top level of the hierarchy. It is connected to the second level node—namely, the CRSP operations center node (referred to as the supervisor lane in Figure 3 shown in black)—with a point-to-point link. The CRSP lanes (i.e., container, pallet, and rolling stock lanes shown in black) appear at the third level, they are each connected to the supervisor lane with a point-to-point link.

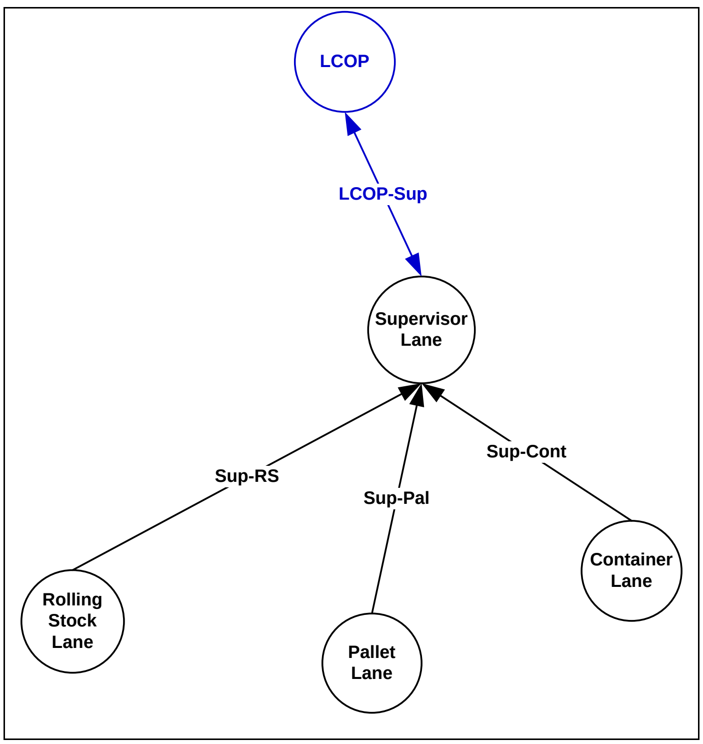

Figure 3. Hierarchical Network Topology (Best Viewed in Color)

The labels on the arcs in the network represent the communications channels (i.e., “LCOP-Sup” is the channel for the LCOP and supervisor lane, “Sup-Cont” is the channel for the supervisor and container lane, “Sup-Pal” is the channel for the supervisor lane and pallet lane, and “Sup-RS” is the channel for the supervisor lane and rolling stock lane).

b. Star Network Structure

The Star network structure, delineated in Figure 4, delineates a topology in which each of the four nodes of the network within the CRSP is connected to the network-centric LCOP node with a point-to-point link. The resulting structure has four communications channels in a hub and spoke arrangement. In this context, the LCOP node is the hub and the CRSP lanes nodes (i.e., container lane, pallet lane, rolling stock lane, and supervisor lane) are the spokes.

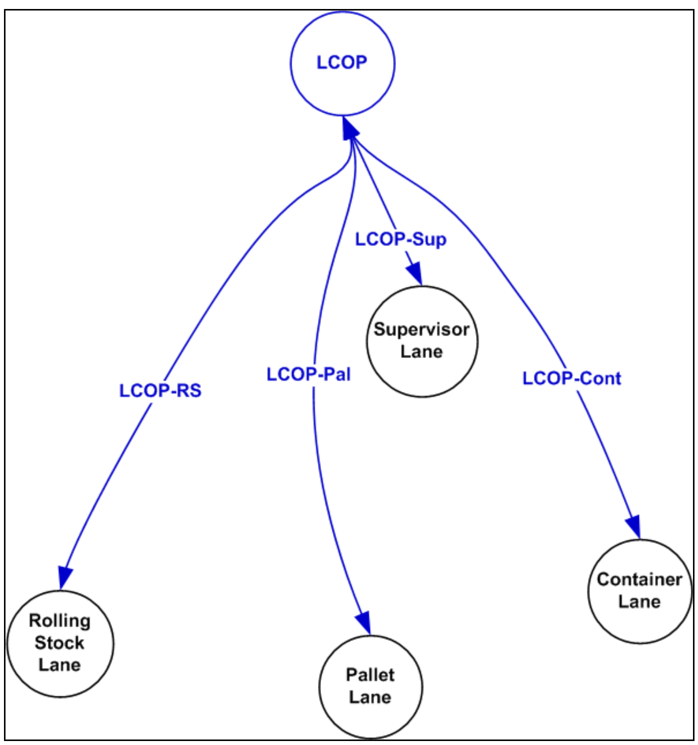

Figure 4. Star Connected Network Topology (Best Viewed in Color)

c. *Hierarchical-Star Network Structure*

The Hierarchical-Star network structure, shown in Figure 5, represents a type of network topology that is based upon the physical star topology connected together in a hierarchical fashion to form a more complex network. The LCOP (top level central node) is the hub of the top level physical star topology. The top level is shown in blue representing the interactivity between the CRSP lanes and the LCOP. The operations center (second level central node) is also attached to each spoke node in a hierarchical manner. This structure is shown in black representing, point-to-point links within the CRSP. This network provides a more collaborative environment that enables direct communications with any and all stakeholders.

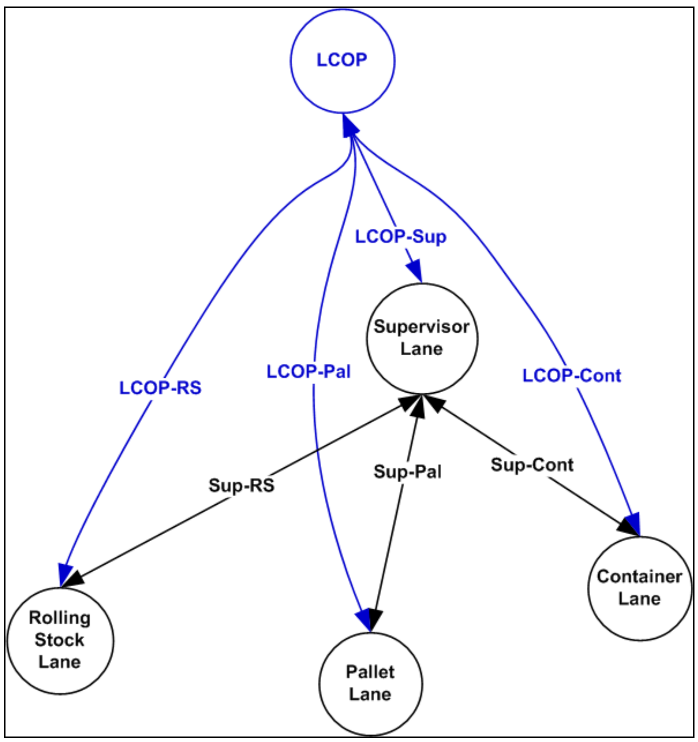

Figure 5. Hierarchical-Star Network Topology (Best Viewed in Color)

4. Required Capabilities

A capability is the ability to achieve an effect to a standard under specified conditions using multiple combinations of ways and means to perform a set of tasks (NCE JFC, 2005). The capabilities presented below will be measured against the current and programmed capabilities to determine capability gaps. These capabilities are derived from the NCOE JIC, JL (D) JIC, and Army Transportation Corps FAA.

- ***ITV***. Actions at the CRSP dictate how effectively and efficiently equipment and supplies get to their ultimate destination. Thus, the JF depends on CRSP operators that are fully capable of establishing and maintaining visibility of assets and cargo as they move through the theater distribution network.
- ***Cargo operations***. Terminal cargo operations are capable of handling any capacity of sustainment-based operations with cargo handling equipment and personnel. CRSP cargo operations must possess the capability to receive from and transship to any mode of military and commercial transportation.
- ***Velocity management***. Cargo handling is a critical element of the global distribution system and, therefore, possesses all of the information capability and interconnectivity required to manage and maintain CRSP operations. Members of the CRSP are connected and responsive to the distribution system and managers, possessing ITV and cargo documentation capability required for maintaining the tempo and flow of the battlefield distribution system.
- ***Ability to collaborate***. Collaboration tools, such as logistics information systems and joint distribution information systems, are in place. These provide CRSP members with real-time visibility of user requirements, distribution resources, operational and environmental conditions, and the current relevant situation.
- ***Ability to share situational understanding***. This capability includes the ability for the CRSP members to spread information in a timely and accurate fashion to enhance situational understanding and awareness via an LCOP.
- ***Ability to identify/store/share/exchange data/information***. Finding, storing, sharing, and providing, information. Search and retrieval networked communications capabilities are available to stakeholders (e.g., authorized interagency and coalition forces, international organizations, commercial entities, and non-governmental organizations) to quickly and accurately access the relevant LCOP information.
- ***Ability to process information***. Authorized users acquire timely, reliable access to relevant information sources. This capability includes capturing, creating, and displaying information with local (e.g., handheld) tools while disconnected from the net.

B. LOGISTICS BATTLE COMMAND

The LBC model is a low-resolution, object oriented, stochastic, and discrete event model programmed in Java that incorporates Simkit as the simulation engine (Buss 2001). The LBC model can serve as a stand-alone analysis tool, or as a dynamic logistics module that can be fully integrated with analysis supported by an existing combat model.

The LBC stand-alone model is intended to support sustainment analysis in situations where a combat model is not necessary or resources are not available to employ a combat model. In the stand-alone mode, the model will require data inputs that replace data obtained from the combat model. The model can either be used iteratively with another analysis tool or to be run for the entire length of the analysis time period. When operating in the integrated mode, the LBC model will act as a module of the combat simulation with fully automated data exchange. In general, LBC will provide a detailed logistics representation to the combat model by responding to events endogenous to the simulation and by interjecting sustainment effects.

The current LBC version is the result of substantial revisions and expansion by TRAC-MTRY with TRAC-LEE to improve the functionality and usability of the model as an analysis tool for sustainment battle command analysis. Essentially, LBC functionality includes planning and decision support features to enable a simulated sustainment decision maker to monitor the logistics LCOP, forecast demand for most classes of supply, and initiate and adjust missions to distribute supplies and perform sustainment functions. The LBC model uses network architectures to represent the distribution pipeline to summon sustainment planning and execution representing the end-to-end flow of resources from supplier to point of consumption. Specifically, it represents the distribution network as defined by user input and explicitly represents distribution operations by scheduling bulk distribution from theater to brigade using the forecasted demands and user-defined distribution network. Additionally, it receives situation updates on non-recurring demand items, and then schedules and arranges for efficient distribution of those non-recurring demand items.

The LBC model uses nodes and arcs to represent the different networks of the joint distribution system. The LBC model accomplishes this through three layers of network representation: the transportation, communications, and planning networks.

The bottom layer is the transportation network. This links the LBC model to the physical area of operations representing the geographical distribution of supplies, and allows for dynamic route planning. The LBC model uses nodes (i.e., storage, maintenance, supply, medical, and field services) and arcs (i.e., modes of supply and transportation) to spatially represent the physical network. Algorithms within LBC generate missions including determining the best methods and routes for transporting supplies to the end user while accounting for changing battlefield conditions.

The middle layer is the communications network. This represents an arbitrarily complex communications network of the distribution system linking leaders and Soldiers to all applicable stakeholders including the LCOP. This communications network carries the data of the distribution system information network and links the planning and transportation layers in the LBC. The LBC model uses nodes to represent stakeholders and arcs to represent connectivity between nodes.

The top layer is the planning network. This represents the data of the distribution system information network. The LBC model uses a task network to link the sustainment planning to execution. The planning network in LBC allows for monitoring any deviations between the sustainment execution and the sustainment plan, and also allows for dynamic sustainment re-planning.

The LBC model runs from an XML file created from input in an Access database, or an Excel spreadsheet. There are 24 tables in the input file for the current version of the stand-alone LBC model. These tables contain information required to execute a scenario. Only the data tables related to this research will be discussed further. For more information on other tables, see the LBC User's Manual available from https://diana.nps.edu/ds/.

- ***ScenarioData***: The ScenarioData table is the primary driver for the simulation. Key elements specified in this table include the length of the scenario, the number of replications to perform, and the scenario type to indicate if the LBC is running in its stand-alone mode or as a module supported by an existing combat model.
- ***ForceStructure***: The ForceStructure table defines the number and type of systems in the scenario, as well and the owning unit of each system.
- ***ConsumableType****:* The ConsumableType table defines the types of consumables in a scenario.
- ***Channel****:* The Channel table defines the effectiveness of the different communications channels in the communications network for the scenario. Key elements in this table include the probabilities of successful communications and the message latencies in hours.

- ***Communicator****:* The Communicator table determines whether or not a specific node in the communication network is able to relay information received from other nodes, given connectivity between nodes as defined in the Channel table.
- ***CommunicationsEquipment****:* The CommunicationsEquipment table defines the communications network, represented as node and arcs, and the capability to transmit and receive messages.
- ***SimpleProvider****:* The SimpleProvider table lists the names of the providers and consumers in the scenario, defines the Communicator for each of the providers, and the speed (in hours) at which these providers update the LCOP.
- ***SimpleProviderConsumables****:* The SimpleProviderConsumables table contains the initial quantity and logic for consumption of each consumable type at each provider.
- ***RandomTransportationDelay****:* The RandomTransportationDelay table defines the probability distributions for how long it takes to get from one location to another when using random delays. The key elements of the RandomTransportationDelay table are the source of the shipment, its destination, and the distribution shapes and parameters for generating random variates.
- ***TaskNode****:* The TaskNode table defines nodes in a task network. Each node represents an activity or task that requires dedicated resources and a period of time to complete. Key elements are the name of the node, the providing unit assigned to the tasks, the type and quantity of resources required to fulfill the task, the name of the task associated with the node, the consumable type and quantity, the unit receiving these consumables, and the task start time.
- ***TaskNodeDuration****:* The TaskNodeDuration table specifies the probability distributions for generating random variates to represent the times for completing tasks.
- ***PrecedenceArc****:* The PrecedenceArc table defines the precedence relations between two tasks in the task network defined on the TaskNode table.
- ***Output****:* The Output table establishes the destination file for writing.

C. TRANSPORTATION NETWORK DEVELOPMENT

As previously mentioned, the transportation network links the LBC model to the physical AO. This network is essential to model operations within the CRSP used in the research scenario. The essential LBC input tables required to create and accurately represent the transportation network are the *TaskNode, TaskNodeDuration,* and *PrecedenceArc* tables. The methodology used to develop the transportation network and to represent sustainment missions are the Program Evaluation and Review Technique (PERT) and the Critical Path Method (CPM) models. PERT and CPM are project management techniques that use network models to represent tasks or activities. Tasks or activities are depicted as nodes on the network, and precedence relations that signify the order of operations are depicted as arcs between the nodes.

Once the scenario is selected, the specific tasks or activities are identified to represent the nodes in the network, and their sequencing requirements are shown as arcs. These nodes and arcs were captured in a network diagram representing the transportation network.

1. Transportation Network Explained

The transportation network delineated in Figure 6 represents the LBC implementation of the scenario in accordance with the CRSP concept of operations. Two dissimilar types of convoys, from different points of origin, move to a CRSP to deliver and pick up cargo. Theater transportation assets originating from the theater base are uploaded with replenishment and sustainment items, while BSB transportation assets are loaded with retrograde items. Upon arrival at the CRSP, the convoys move to the respective lanes based on the cargo being delivered. The container, pallet, and rolling stock lanes are referred to as "Cont Lane, Pal Lane, and RS Lane" respectively in Figure 6. Given this research focus, this experiment considers operations within the CRSP; hence, the analysis focuses precisely on the cargo entering and leaving the CRSP and does not account for CLP operations outside the CRSP (see Figure 6: start time and stop time). In this case, convoys arrive randomly at the CRSP over a predetermined number of days. The statistics collection period begins when the first truck arrives at a CRSP lane and continues until no trucks remain in the CRSP. Cargo delivered by theater assets is downloaded, and then uploaded onto BSB convoys for delivery to the points of need. Upon completion of downloading and uploading cargo, convoys depart the CRSP to return back to their points of origin.

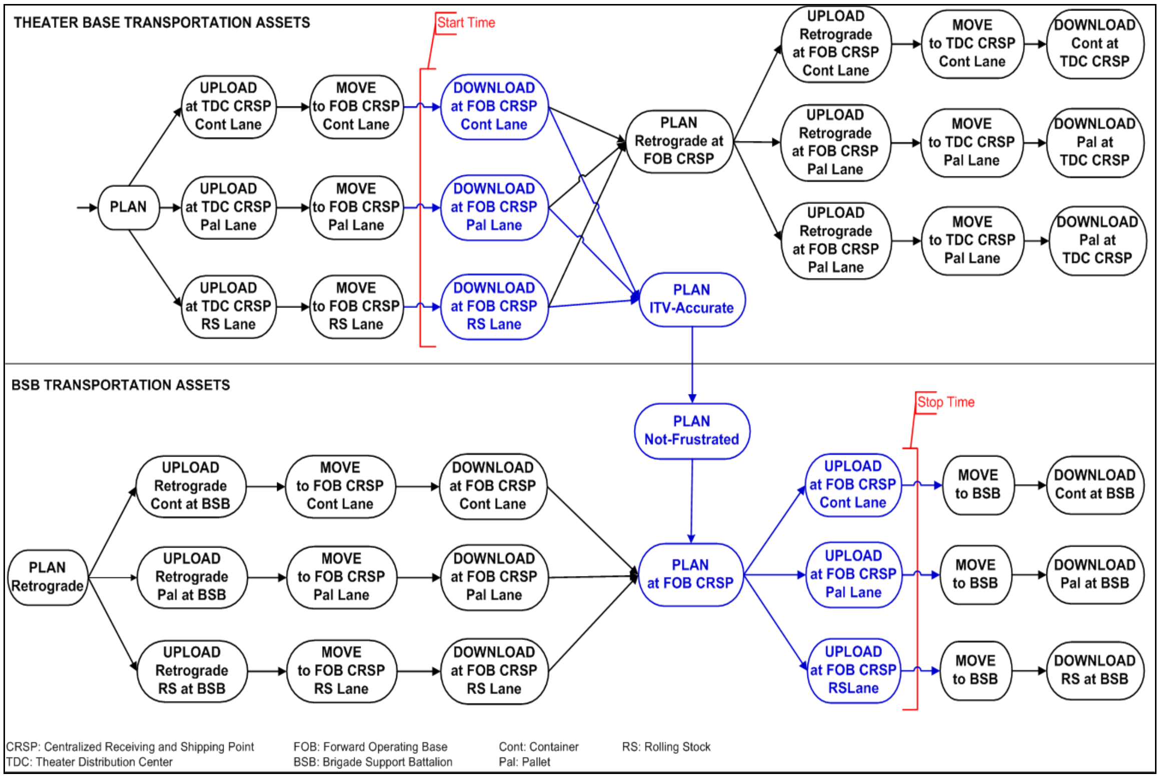

Figure 6. Transportation Network Diagram (Best Viewed in Color)

2. LBC Tables Creation

The current version of the LBC stand-alone model requires that all of the information required to represent the transportation network is created manually using Excel. Much work must be done to create the *TaskNode, TaskNodeDuration,* and *PrecedenceArc* tables, described previously in this chapter. For this study's scenario, as depicted in Figure 6, all of the PERT information for a single convoy translates to rows and columns of information in each of these tables. A single convoy contains 42 to 49 rows of information and up to 14 columns in each of these tables, altogether representing thousands of pieces of data required. To create 1320 convoys, the maximum number of convoys in a single run of LBC for this research, a Visual Basic (VB) code in Microsoft Excel was developed by the author. This code greatly decreases the time required to construct a scenario, and also greatly reduces the possibility of data entry error. All of the essential information required in these three tables is generated in an automated manner, and the data are saved in an LBC model input file. With this enhancement, tables can be created in approximately 60 to 90 seconds, depending on the computer performance, instead of requiring several hours of effort to enter the data manually.

D. CONSTRAINTS, LIMITATIONS, AND ASSUMPTION

This section describes the constraints, limitations, and assumptions. Constraints are the restrictions that limit the options in conducting the study. Limitations are an inability to fully investigate the study issues due to model limitations. Assumptions are those statements related to the study that are taken as true in the absence of facts, often to accommodate a limitation (TRAC Constraints, Limitations, and Assumptions Guide, 2006).

1. Constraints

- LBC model improvements are limited to those achievable in a three-month development window.

2. Limitations

- The model currently lacks an integrated design of experiments interface that enables a quick determination of alternatives.
- The task network in the model is limited to four specific events: Plan, upload, move, download. Furthermore, the sequence for the last three events cannot be altered due to model limitations.
- The current version of the model cannot simulate the reallocation of resources within the CRSP based on communication messages.
- The time required for an upload and download task is based on SME input because performance data for operations within a CRSP are not readily available.

3. Assumptions

- The quantity of trucks per convoy remained fixed. Since the scenario takes place inside a secured area, the simulation does not consider attrition due to enemy contact or maintenance losses.
- Time in CRSP begins when the first truck moves to a specific lane within the CRSP and ends when the last truck departs the CRSP.

- Each cargo unit has an equal probability of being identified as frustrated. The probability distribution for cargo identified as frustrated remained the same throughout the experiment.
- Convoy transition times between points of origin to and from the CRSP remain constant.
- Service discipline at the CRSP is first-come-first-served (FCFS), as there is no priority handling between primary versus retrograde cargo.
- Time in the CRSP increases by a fixed amount if cargo is missing ITV information or has inaccurate information. This represents time to sort out the information for frustrated the cargo.

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IV. MEASURES OF EFFECTIVENESS AND DESIGN OF EXPERIMENTS

The first section of this chapter defines the Measures of Effectiveness (MOE) of interest for analysis in this experiment. The next section describes Design of Experiments (DOE), and the development of design points, followed by a discussion of the selection of factors included in the experiment. The chapter concludes with a brief discussion of procedures developed to create the scenario files based on the DOE, followed by essential considerations in execution of the simulation runs.

A. MEASURES OF EFFECTIVENESS

The three MOEs of interest for analysis in this research are Velocity, Reliability, and Visibility. These MOEs are quantitative measures of the performance of the model that indicates how well the three different network structures meet the specific mission task in the given scenario. Together they to measure the improvement of degree of perfection in accomplishing the required capabilities identified during the FAA phase of the CBA process. These MOEs were derived directly from concept specific attributes listed in the JL (D) JIC in order to provide the linkage from the specific mission tasks to the estimated operational outcomes for each scenario (CJCSM 3170.01C, 2007). Similarly, the intent for the selection of these based on joint concepts attributes is to provide decision makers with the traceability of capability gaps to required capabilities. Hence, these MOEs provide the means to answer the research questions posed in the introductory chapter and will be defined precisely.

1. MOE 1: Velocity

Velocity is the speed at which convoys are processed in the CRSP. Speed is only one aspect of velocity. Convoys must be processed with the right resources at the right speed. Velocity is measured in terms of CRSP response. Velocity is expressed as the mean time in CRSP which accounts for waiting plus time receiving service. As the mean time in CRSP decreases, velocity increases.

2. MOE 2: Reliability

Reliability is the degree of assurance or dependability that CRSP operations will consistently meet cargo demands under established conditions to specified standards. Reliability measures the variability of the mean time in CRSP and the mean difference in area of visibility.

3. MOE 3: Visibility

Visibility represents the capacity to determine the status, location, and direction of flow of materiel. Visibility requires the availability of timely, accurate, and usable information essential to the maintenance of the LCOP with the overall joint distribution stakeholders. It quantifies mean difference in the area between the ground truth stock levels at the CRSP lanes and the LCOP levels. Shown in Figure 7 is a pictorial representation of the difference in area between the entities. The dashed blue line represents the lane stock level, the solid black line represents the LCOP level, and the shaded areas correspond to times when visibility is poor. As the mean difference in the area decreases, visibility improves.

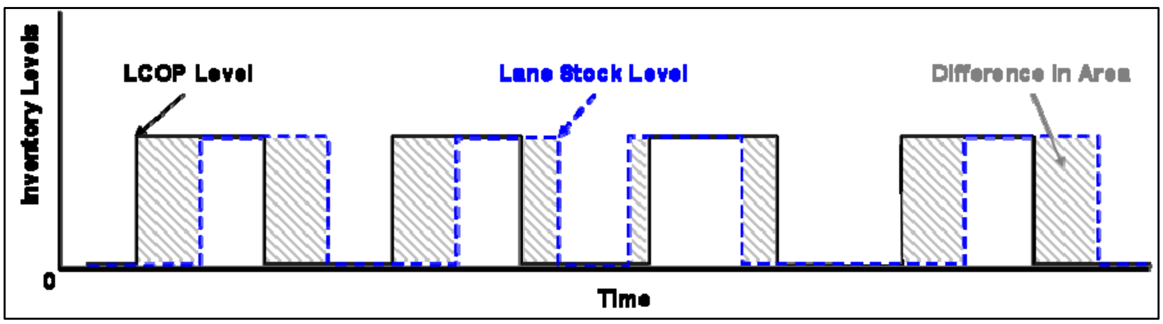

Figure 7. LCOP and CRSP Lanes Difference in Area (Best Viewed in Color)

B. DESIGN OF EXPERIMENT

This research leverages experimental design techniques to explore the simulation model results and to assess how selected input parameters or factors changes impact the model's output. The design for the experiment is constructed in a matrix, where every column corresponds to a factor, and the entries within the column are settings or factor levels for this factor. Each row represents a particular combination of factor levels which defines a scenario or design point. This matrix is called the design of experiment (DOE) which is the mechanism used to vary the settings of these factors of interest, conditioning the model to answer the research questions through the use of simulation and data farming. Output from the simulation runs is analyzed to evaluate how the various input factors affect the response surface or MOE across the range of scenarios (Sanchez, 2006).

1. Factors

The factors in the simulation experiment of this research are divided in two groups: decision factors and noise factors. Decision factors, also known as controllable factors, are those factors that represent controllable action options to decision makers for the real world problems. Noise factors, also called uncontrollable factors, are those factors not easily controllable or controllable only at great expense in the real-world setting; however, one could benefit by observing the influences these factors have on the experiment outcome (Sanchez, 2000). The decision factors considered are ITV-available, ITV-accuracy, LCOP-update, probability of communications, latency, and communication relay capability. These factors all potentially influence network capability for the scenario. The noise factors are resources available, convoys per hour, and convoy composition. Varying these factors allows for examining the impact of network capability aspects across a broader range of potential operating conditions. These factors were derived directly from concept specific attributes listed in the NCOE JIC (2006). This approach for factor selection is appropriate for this research because it allows for the assessment of the NCOE capabilities based on the concept-defined attributes. Below is a discussion of the factors of interest.

a. ITV-Available

ITV-Available represents the probability that CRSP personnel are provided with timely, reliable access to the ITV data of cargo. This continuous factor accounts for the information provided by the AIT systems (e.g. RF tags) to the CRSP personnel and assigns a time penalty for servicing the cargo based on the ITV data availability. The higher the probability, the faster the cargo will be processed within the CRSP. This factor is considered on all three communications network structures. The factor low level is 0.1, and high level is 1.0.

b. ITV-Accuracy

While ITV-Available controls the probability that a transmission of cargo data is received, ITV-Accuracy represents the likelihood that the transmission is received correctly. In other words, this continuous factor accounts for the accuracy of the cargo's ITV data available and assigns a time penalty for servicing the cargo based on this accuracy. This factor is considered on the three different network structures aforementioned. The factor low level is 0.1, and high level is 1.0.

c. LCOP-Update

LCOP-Update is the rate in hours at which a node (i.e., a provider or CRSP lane) updates the LCOP, given connectivity (a communications channel) between the node and the LCOP. This factor determines the quality of a net-enabled LCOP based on ITV-Available, ITV-Accuracy, and network reliability. This continuous factor is considered on the three different network structures aforementioned. The factor low level is 0, and high level is 0.25.

d. Probability of Communications

Probability of communications (P[Comms]) corresponds to the probability of successful communication between connected nodes in the network. It emulates link reliability and degradation in the network. This continuous factor represents the different communications channels in the network. Hence the Hierarchical and the Star network structures contain four dissimilar P(Comms), and the Hierarchical-Star network structure contains seven P(Comms) related to the communications channels in the network, as described in Figures 3, 4, and 5. The factor low level is 0, and high level is 1.0.

e. Latency

Latency refers to the message transmission delay in hours for a given communications channel in the network. This continuous factor is considered on the three different network structures aforementioned. The factor low level is 0, and high level is 0.25.

f. Communication Relay Capability

Communications Relay Capability represents the capability, or lack thereof, of a node in the communications network to relay information received from other nodes given connectivity between nodes represented as a communications channel. This Boolean factor, considered a categorical factor, is either true or false. In this context, if a node has the capability available to relay, it can relay organic information received from other nodes, as well as its own individual information, to other nodes in the communications network.

g. Resources Available

Resources are things required to perform tasks. The Resources Available factor accounts for the amount of MHE available (i.e., Rough Terrain Container Handlers [RTCH], forklifts, and ramps) for operations at the CRSP. This quantitative factor represents the proportion out of a maximum of 16 pieces of MHE, expressed in number of available pieces for the mission. This factor is considered on the three different network structures aforementioned. The factor low level is 0.1, and high level is 1.0. These continuous values were translated to discrete values.

h. Convoys per Hour

Convoys per hour are the amount of convoys arriving to the CRSP at a steady pace in an hour interval. This factor explores 3 distinct arrival rates: one convoy per hour (every hour), two convoys per hour (one every 30 minutes) and three convoys per hour (one convoy every 20 minutes). This factor is considered on the three different network structures aforementioned.

i. Convoy Case

Convoy case represents the percentage of commodities such as pallets, containers, and rolling stock being delivered by the convoy. This categorical factor has three different cases defined below:

- Case 1: 30% of pallets, 30% containers, and 40% rolling stock.
- Case 2: 36% pallets, 36% containers, and 28% rolling stock.
- Case 3: One-third of each, pallets, containers, and rolling stock.

2. Nearly Orthogonal Latin Hypercube Design

Several designs are possible; nevertheless, the Nearly Orthogonal Latin Hypercube (NOLH) design has several advantages for the analysis. First and foremost, NOLH designs are extremely flexible and efficient; this makes them suitable for experiments where there are many factors of interest. This space-filling technique, where the design points are scattered throughout the experimental region, allows the analyst to identify the linear and nonlinear relationships, as well as interactions, and provides greater detail about the form of these relationships than other designs, such as those sampling only at low and high factor levels. Minimizing the correlation between factor columns to create a nearly orthogonal design matrix simplifies the analysis by making it easier to separate the impacts of different model terms. Additionally, the NOLH is very flexible when creating an efficient design for the experiment. Factors can be easily added or removed, as well as the settings or levels for those factors can be changed conditioning the model to provide more insights into the response surface or to develop an entirely new design (Sanchez, 2006; Kleijnen et al., 2005).

The NOLH used for this research was constructed using the NOLHDesigns_v4.xls spreadsheet created by Professor Susan Sanchez (2005) based on the designs of Cioppa (2002) (see also Cioppa and Lucas, 2007). This tool consists of worksheets that create a DOE for a specific number of factors. Moreover, the spreadsheet features are aligned with the NOLH desired properties; particularly, it ensures a space-filling design while avoiding conflicts associated with multicolinearity. Note that while the base NOLH designs are intended for factors with continuous levels, the spreadsheet allows these to be rounded. The orthogonality properties of the designs may change when rounding occurs, so it is a good idea to check the pairwise correlations before implementing the design.

Three NOLH DOEs were constructed, one for each of the network structures being explored in the experiment, for a total of 771 design points. The NOLH design for the Hierarchical and Star connected network structures consisted of a 257 x 15 matrix with a maximum pairwise correlation of 0.0952 each, and the design for the Hierarchical-Star network structure consisted of a 257 x 19 with a maximum pairwise correlation of 0.0646. The pairwise scatterplot of the design point for the Hierarchical-Star network structure is contained in Appendix, Figure 47 demonstrating the space-filling and near-orthogonality properties of the NOLH design developed.

Cioppa and Lucas (2007) use the criteria of maximum pairwise correlation less than 0.03 to classify a matrix as nearly orthogonal. It is possible to reduce the values attained in this research to these levels using more design points, e.g., by assigning the input factors to different sets of columns and stacking two or more designs. However, given the time required to perform these runs and the relatively small maximum pairwise correlations, the values achieved in this research design were considered low enough given the resolution of the model

C. EXECUTION OF SCENARIOS

1. LBC Model Input File Creation

In Chapter II, it was articulated that current version of the LBC model requires manual creation of the scenario input file, an extremely tedious and time-consuming process. In this context, every design point represents an LBC model scenario file, meaning that for this research it was required to create one scenario file per every design point in the DOE. Due to the current LBC model limitations, VB code in Microsoft Excel was developed by the author to automate the implementation of this research experimental design and creates scenario files for every design point.

The VB code reads the DOE and translates the design point data to useful data in accordance with LBC model naming and syntax conventions. Next, the VB code updates the LBC scenario file with the design point data and uses the factors levels to create the transportation network leveraging on the VB code aforementioned in Chapter II. Finally, the LBC model input file is saved with a unique name reflecting a design point. This overall process is repeated until all design points are exhausted and LBC input files are created. Production of the 771 design points for this experiment was completed in approximately 13 hours using a personal laptop with 3G of RAM.

2. Terminating Simulations

Even though all computer simulations are by nature terminating, the system being modeled may be a terminating or a steady-state simulation. Events driving terminating simulation cease occurring at some point on time or when a specific event has occurred, whereas the steady-state continues indefinitely (Kleijnen et al., 2005). Given that all of the simulations in this research start at a defined state and end when they reach some other defined event, they are terminating simulation models. Accordingly, the initial state of the model at the beginning of the simulation is that all of the CRSP lanes and all of the resources are at idle. The system remains idle until convoys begin to arrive in the CRSP. There are a fixed number of convoys for each design point defined by the convoys per hour factor: 440 convoys for one convoy per hour, 880 convoys for two convoys per hour, and 1320 convoys for three convoys per hour. The actual times that convoys arrive at the CRSP are stochastic, according to the specified arrival rateThe system terminates when all of the convoys are loaded and depart the CRSP. Since this research experiments with terminating simulation models, each experiment comprises multiple replications per design point (each replication is treated as a sample) over a period of interest defined by the terminating condition using a different random seed for each experiment. This procedure enables statistically independent and unbiased observations to be on the response variables of interest in the system over the time period simulated (Sanchez, 2006; Kleijnen et al., 2005).

3. Computing Resources

Simulation analysis requires scenario productions runs. Simulations involving deterministic processes require only a single run per scenario, compared to stochastic processes that require multiple runs per scenario. Although the LBC model is capable of running on standalone computers, it is necessary to execute the simulation runs using a computing cluster. These production runs were executed by Dr. Paul Sanchez, Senior Lecturer in the Operations Research Department at the Naval Postgraduate School, on the Simulation Experiments & Efficient Designs (SEED) Center computing cluster located on the NPS campus in Monterey, CA. The experiment involved 10 runs for each of the 257 scenarios for a total of 7,710 runs. In addition, simulation runs were executed for a secondary experiment of 10 runs of 96 scenarios for each of the three communications totaling 2,880 runs. This secondary experiment was used for validation purposes, and will be discussed in more detail in Chapter V. In all, this amounts to 10,590 runs. The time to complete each scenario differed dramatically based on the design point. Some scenarios were complete in 10 minutes, while others took up to approximately 9 hours.

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V. ANALYSIS

This chapter describes the means and procedures used for the analysis, followed by an in-depth analysis of data sets. It begins with an overview of the methods, tools, and techniques used during the analysis. The next two sections present the methodology utilized to explore the data sets and significant findings from the analysis that answers the research questions. This chapter ends with significant observations based on comparison of the MOEs.

A. METHODOLOGY, TOOLS, AND TECHNIQUES

1. Methodology

To investigate the impact of network-enabled capability the same analysis methodology is applied to analyze the Hierarchical, Star, and Hierarchical-Star networks structures in the given scenario of this experiment. Upon completion of the simulation execution, several tools, methods, and procedures were used to explore and maximize insight into the data set. Graphical, multiple regression, and Classification and Regression Trees (CART) analysis techniques were performed to uncover the underlying structure for each scenario, extract important factors, and detect outliers and their potential impact on subsequent analysis. Furthermore, these techniques were employed to develop parsimonious models, and to determine favorable factor settings. CART and graphical analysis were applied to confirm the validity of the model behavior and to gain insights about significant factors influencing further analysis.

2. Analysis Tools

a. JMP Statistical Discovery Software

JMP Statistical Discovery Software, a product of the SAS institute, is the statistical software package used to conduct cleaning and analysis of the data collected throughout the analysis portion of this research. JMP was chosen because its data visualization feature allows the user to interactively investigate data, refine and understand the analysis results in a dynamically linked spreadsheet and graphical environment. In addition, JMP provides the user with the capability for saving and revisiting graphics or data tables of interest in a journal (Sall, Creighton, & Lehman, 2007). Additional information on JMP can be found on http://www.jmp.com/software.

3. Analytical Techniques

A variety of analysis techniques are available for exploring and analyzing model output data. This analysis focuses on techniques to examine and understand the scenario, explore the datasets, and detect structure in the relationships between factors focused. This research employs three techniques: graphical analysis, multiple regression, and CART. They are used in complimentary manner to help answer the research questions of interest. Subsequent paragraphs provide a brief description of each technique used throughout the analysis, but is left for the reader to explore if further information is desired.

a. Graphical Analysis

Graphics are a fundamental part of data analysis, used in initial data exploration, model development, and also communicating information. Graphical tools used during this research include scatter plots, histograms, probability plots, contour plots, line graphs, and leverage plots. Analysis of the data produced throughout this research using such graphical tools provides the means to gain insights into the data set for model selection, factor selection, outlier detection, factor effect determination, and statistical model validation. In addition, these graphical tools provide a convincing means of presenting and communicating this research results and its underlying message.

b. Classification and Regression Trees

CART is an alternative to equation-based methods with fewer assumptions. CART offers defined rules that recursively split the data set into homogeneous subsets in accordance with the relationship between the response variable and the predictors. Each split looks one step ahead to find the "best possible split," by considering all possible cuts or groupings given the current state of the tree to select a partition with the largest likelihood-ratio chi-square statistic (Gaudard, Ramsey, & Stephens, 2006). Trees are useful for exploring the data of thousands of simulation runs over many factors as well as communicate the results. However, there are a few limitations associated with this non-parametric tool. For example, if there is a strong linear relationship they are poorer at fitting concise models to continuous response surfaces. Hence, this useful tool is used in conjunction with results from other techniques such as multiple regressions to gain insights about the output of the simulation model.

c. Multiple Regression

Multiple linear regression analysis is a statistical process that allows examining the effect of many different factors on some outcome at the same time. The general purpose of it is to learn more about the relationship between several independent or predictor variables and a dependent variable (Montgomery, Peck, & Vining, 2006). This research applies this practical technique to examine the effects of the factors of interest, as well as their interactions with other factors, to determine which have the greatest influence on the defined MOE. Moreover, multiple regression models may confirm the regression tree results concerning which factors are more influential, or may allow more concise description of the simulation model by suggesting different combinations that not yet been examined (Kleijnen et al., 2005).

B. ANALYSIS FOR TERMINATING SIMULATIONS

Since queuing theory certifies that resource utilization and flow rates (convoys per hour) have most meaning for successive time interval during the simulation, the output is analyzed to determine the impact of these factors and how they affect the analysis. After the experiment is complete, these two factors are combined into a single term called traffic intensity. This does not directly correspond to the traffic intensity in a mathematical model of an M/M/1 queuing system, where a traffic intensity of 1.0 or more leads to infinite queue build-ups. Nonetheless, higher traffic intensities are associated with more congestion in the CRSP. (Note that an alternative experimental design could vary convoys per hour and traffic intensity, rather than conveys per hour and resource utilization, as the factors to facilitate the analysis; see Kleijnen et al., 2005). Accordingly, traffic intensity is the ratio between convoys per hour and resources available, which measures the amount of congestion in the CRSP conditioned once the CRSP first starts receiving cargo until all cargo is processed. During periods in which the CRSP is idle an arrival can always be served immediately. Figure 8 shows a scatter plot of mean time in CRSP vs. traffic intensity for the Hierarchical network structure. This plot clearly illustrates the influence of these data points with traffic intensity greater than 1.0 (depicted in red).

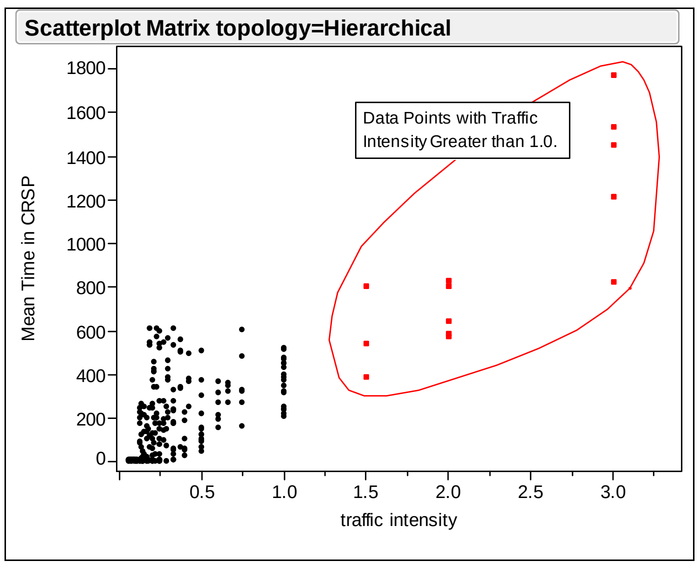


Figure 8. Scatterplot for Mean Time in CRSP by Traffic Intensity (Best Viewed in Color)

Further analysis provides insights regarding the simulation system used for this research. Naturally, the system contains an initial transient period. The CRSP starts out empty and idle, so the first convoys will experience least congestion-related delays than later conveys. Because LBC operates on a FCFS basis, a particular cargo-processing time is not influenced by any cargo that arrives later. If the initial transient period is short, then the steady-state processing time distributions may be reached before the simulation terminates.

Six design points were chosen based on their average mean time in CRSP (two low, two medium, and two high) and traces of three of the ten replications are drawn. Plots for Design Point 1 and 31 demonstrate typical behavior for queuing systems with fairly low traffic intensity (Figure 9). Design Point 1 appears to achieve steady-state with no warm-up period; the variation in times indicates that there is a large amount of variability in the system. Design Point 31 has a longer warm-up period and much greater variability, as seen by the differences between the traces for the three replications. Design Point 31 also shows that the times in CRSP are correlated across convoys within each replication.

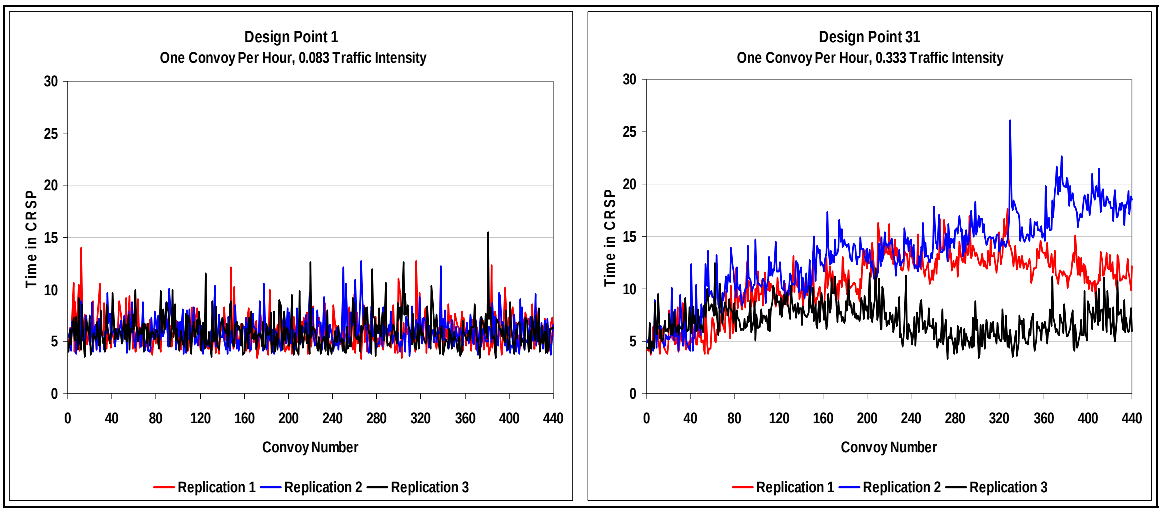


Figure 9. Time in CRSP by Convoy Number Per Replication With One Convoy Per Hour (Best Viewed in Color)

Plots for Design Points 110 and 147 plots show two scenarios with an arrival rate of one convoy per hour, one with low traffic intensity and one with somewhat high traffic intensity (Figure 10). Note that these charts are on a much different scale than those in Figure 9, and that all three replications exhibit very consistent behavior. The plot for Design Point 110 delineates that the system had a long warm-up period; then, the time in CRSP begins decreasing slightly but steadily until the terminating event (440 convoys). It is not clear if this system achieved steady-state. The plot for Design Point 147 outlines a system where handling is of grave concern. This scenario clearly shows a system that is not able to handle the process. The time in CRSP continues to increase, indicating that very large queues are being built up and each successive convey takes longer to process than the last.

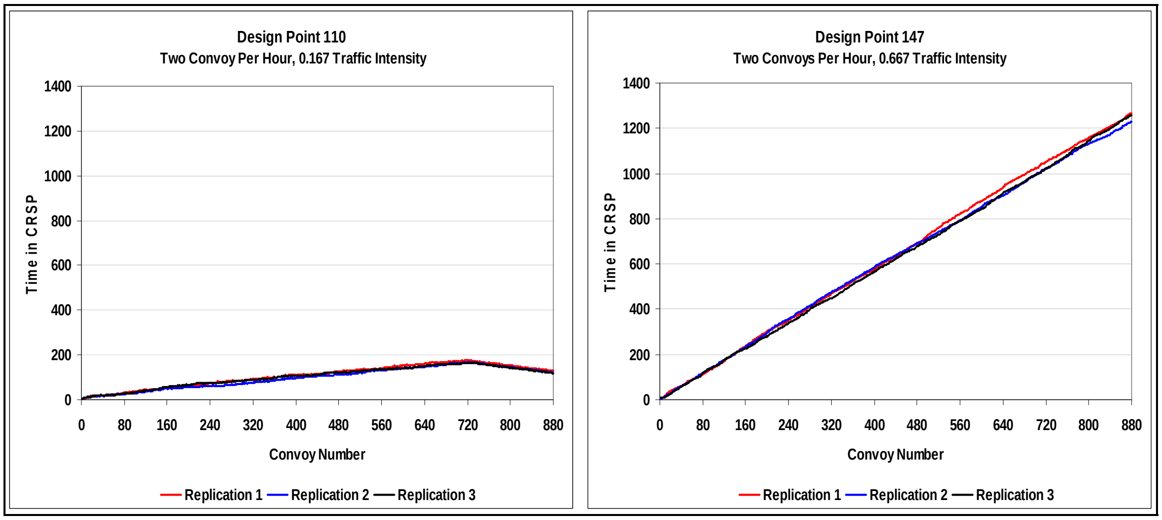


Figure 10. Time in CRSP by Convoy Number Per Replication With Two Convoys Per Hour (Best Viewed in Color)

Plots for Design Points 252 and 239 plots show two scenarios with an arrival rate of two convoys per hour, one with low traffic intensity and one with traffic intensity of 1.5 (Figure 11). The plot for Design Point 252 has a similar behavior to that for Design Point 110. However, the plot for Design Point 239 outlines a system of very unusual behavior. The scenario seems to have a warm-up period, followed by a fixed period of time where time in the CRSP decrease slightly but steadily, but then the system is once again not able to handle the incoming convoys and the time in CRSP rises sharply. It is not evident which conditions lead the system to behave in this manner despite high traffic intensity instead of behaving in a manner similar to that of Design Point 147.

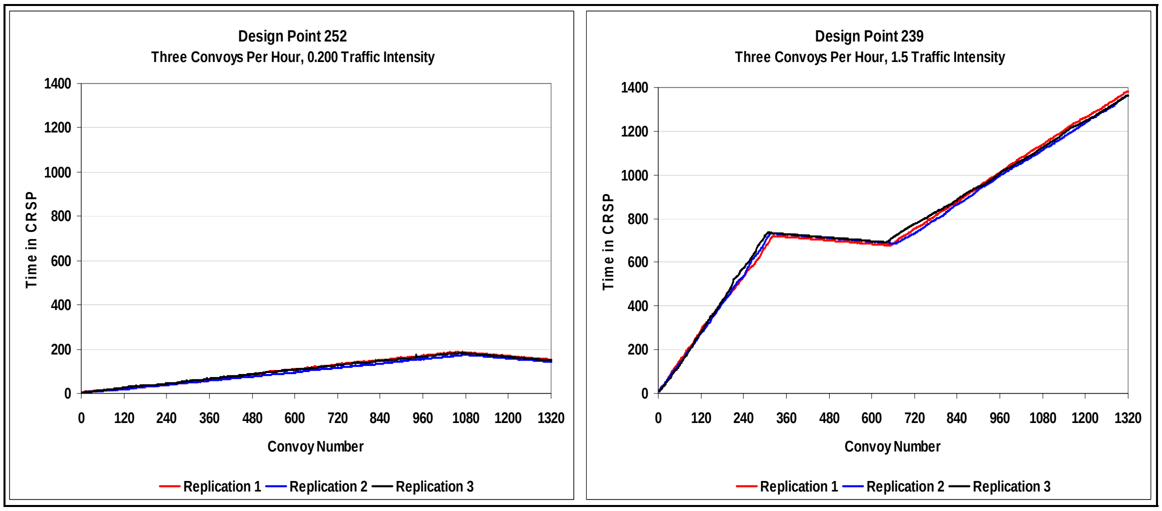


Figure 11. Time in CRSP by Convoy Number Per Replication With Three Convoys Per Hour (Best Viewed in Color)

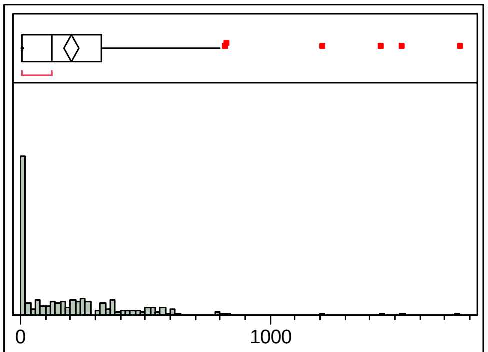
In summary, depending on the scenario conditions some scenarios appear to reach steady-state behavior (with little or no warm up period) while others by no means reach steady-state. This would be of great concern if the goal was to construct numerical predictions of steady-state or long term behavior. Instead, this investigation focuses on comparing three different network structures to identify those factors that have greatest impact on each structure's performance, as well as differences in overall performance for the three structures. Therefore, we can analyze the mean time in CRSP and interpret it as the average time to process the specified number of convoys—recognizing that this may not accurately represent a "typical" time for a convoy. Figures 9, 10 and 11 demonstrate interesting results implying that the system investigated is a complex one that would require further analysis (beyond the scope of this research) to identify which conditions influence the system's behavior and verify that this behavior is not an artifact of underlying model assumptions that might need to be relaxed.

C. MEASURES OF EFFECTIVENESS

1. Hierarchical Network Structure Velocity

The mean time in CRSP distribution plot and summary statistics for the 257 design points is shown in Figure 12. The results reveal that the mean time in CRSP varies from four hours to nearly 440 days. The results are highly skewed; the mean is 204.06 hours, with a 95% confidence interval range from 172.61 hours to 235.51 hours.

Mean Time in CRSP



Quantiles

100.0%	maximum	1759.4
99.5%		1691.3
97.5%		807.2
90.0%		522.5
75.0%	quartile	325.3
50.0%	median	127.9
25.0%	quartile	6.4
10.0%		5.0
2.5%		4.3
0.5%		4.1
0.0%	minimum	4.1

Moments

Mean	204.05877
Std Dev	256.05465
Std Err Mean	15.97225
upper 95% Mean	235.5125
lower 95% Mean	172.60503
N	257

Figure 12. Distribution and Summary Statistics for Mean Time in CRSP, Hierarchical Network Structure

Figure 13 shows the regression tree for predicting the mean time in CRSP. The regression tree consists of seven splits and achieves an R^2 value of 0.792 (ratio of the variation explained by the model to the overall variation in the response). The first split of the data at the top indicates that better mean time in CRSP is attained when the traffic intensity is 1.0 or less. The mean time in CRSP is 166.36 hours across the 244 scenarios with traffic intensity equal to or less than 1.0, compared to the 13 scenarios (rightmost branch) with traffic intensity from 1.5 to 3.0 (inclusive) with a mean time in CRSP of 911.66 hours (82% higher). The subsequent six splits denote subsets with traffic intensity of 1.0 or less. The leftmost branch indicates that the mean time in CRSP is better with traffic intensity less than 0.188; in addition, the mean time in CRSP improves for the scenarios with ITV-Available equal to or greater than 0.242. Across the 20 scenarios with ITV-Available less than 0.242, the mean time in CRSP is 95.49, whereas with ITV-Available of 0.242 or greater the mean time in CRSP for the remaining 76 scenarios is 22.52 hours (74% lower). On the other hand, with traffic intensity in the interval from 0.188 to 1.0 (inclusive) the time in CRSP is 249.80 hours for the 148 scenarios. Subsequent sequences indicate that the mean time in CRSP improves to 103.79 hours for the scenarios with traffic intensity below 0.60 and ITV-Available of 0.492 or greater. Otherwise, the scenarios with traffic intensity equal to or greater than 0.60, the time in CRPS improves from 256.67 hours to 211.67 hours with ITV-Available equal to or greater than 0.723, which is 101.26 hours less than the time in CRSP for the scenarios with ITV-Available less than 0.723.

The results from the regression tree reveal that traffic intensity and ITV-Available have the greatest influence on the mean time in CRSP. Indeed, these results imply that if traffic intensity is near zero there is little queuing in the system; on the contrary, with traffic intensity greater than 1.0 there is a significant amount of queuing in the system. Furthermore, the mean time in CRSP improves with timely and reliable ITV data of cargo even when the CRSP is congested (traffic intensity near 1.0).

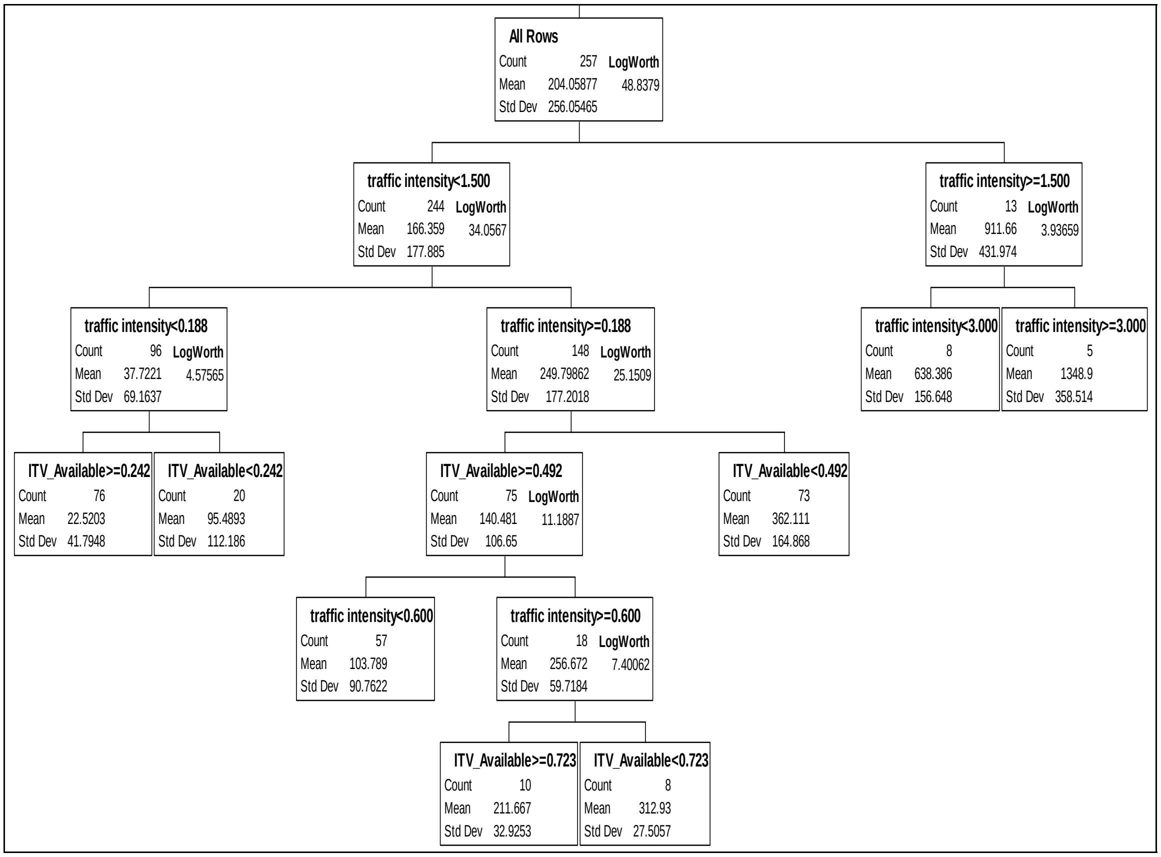


Figure 13. Regression Tree for Mean Time in CRSP, Hierarchical Network Structure

The findings derived from the regression tree clearly identify which factors have greatest influence for the mean response, hence there are used to frame further analysis. Accordingly, a stepwise linear regression method is used to fit regression metamodels (models or approximation functions that characterize the relationship between input and outputs in much simpler terms than the simulation output [Kleijnen et al., 2005]) of the mean time in CRSP as a function of main effects, quadratic effects, and two-way interactions. Several models were constructed and considered but only the final model is shown. The stepwise regression control in JMP was used to identify the most influential factors. This list of statistically significant terms was further narrowed down by considering their practical importance.

The final regression metamodel is shown in Figure 14. The model yields an R^2 of 0.77 and contains two main effect terms and one interaction term. Other models considered include additional terms (other main effects, interactions, and quadratic effects) but explained only 1% more of the variability, thus the simpler model was selected. The results suggest that traffic intensity and ITV-Available are ranked as the two most influential factors. Traffic intensity is the dominant factor as indicated by a large |t-ratio|. These results serve to reinforce and complement those findings of the regression tree.

Whole Model

Summary of Fit

RSquare	0.768786
RSquare Adj	0.766044
Root Mean Square Error	123.8509
Mean of Response	204.0588
Observations (or Sum Wgts)	257

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	12903598	4301199	280.4084
Error	253	3880781	15339	**Prob > F**
C. Total	256	16784379		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	201.08553	16.68101	12.05	<.0001*
ITV_Available	-311.4838	26.82984	-11.61	<.0001*
traffic intensity	389.47486	15.0165	25.94	<.0001*
(ITV_Available-0.50265)*(traffic intensity-0.41024)	-248.2801	48.32956	-5.14	<.0001*

Figure 14. Regression Metamodel for Mean Time in CRSP, Hierarchical Network Structure

To further investigate the how factors and interactions affect the mean time in CRSP, an interaction plot for the regression model is constructed. Interaction plots consist of individual cells or subplots of two lines or curves, one for the factor low setting and the other for the high setting. Solid lines indicate the presence of interaction, curves indicate quadratic effects, whereas broken lines or curves indicate no interaction.

The interaction plot in Figure 15 depicts the interaction term identified in the regression metamodel. The interaction between ITV-Available and traffic intensity indicates that decreasing traffic intensity also decreases the mean time in CRSP. In fact, the decrease in mean time in CRSP is less rapid when ITV-Available is at its highest value (1.0) versus its lowest value (0.004), but setting ITV-Available to its highest value always results in a lower mean time in CRSP.

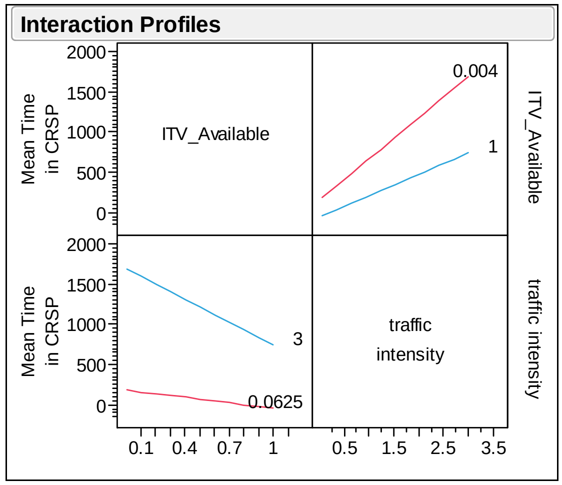


Figure 15. Interaction Profile Plot for Mean Time in CRSP, Hierarchical Network Structure

To validate the results, a different set of scenarios was used. The scenarios used for comparison were developed from a space filling DOE created by U.S. Army Colonel Alejandro Hernandez consisting of 96 design points (See Appendix, Figure 48). A regression tree for the new data again revealed identified traffic intensity and ITV-Available as the most influential factors. Given these facts, in accordance with Kleijnen et al. (2005), the results aforementioned are considered acceptable.

Granted that traffic intensity and ITV-Available are the most significant factors, a contour plot was used to explore more in detail how these factors relate to the mean time in CRSP. Figure 16 shows the contour plot of ITV-Available by traffic intensity. The different contour regions inside the plot (filled in different colors) correspond to different ranges of mean time in CRSP. The plot is read by selecting an intersection between the traffic intensity (x-axis) and ITV-Available (y-axis), and then examining the corresponding mean time in CRSP. This plot complements the metamodel and interaction plot results. For instance, with traffic intensity near 1.0 the mean time in CRSP is less than 400 hours with ITV-Available greater than 0.7. Contrarily, with ITV less than 0.7 the mean time in CRSP could be up to less than 700 hours as indicated by “islands” in the contour. Note that there is a noticeable right motion or curvature of the filled contours. Also, the contour corresponding to mean time in CRSP greater than 1000 hours (rightmost contour depicted in red) is the largest contour in the plot.

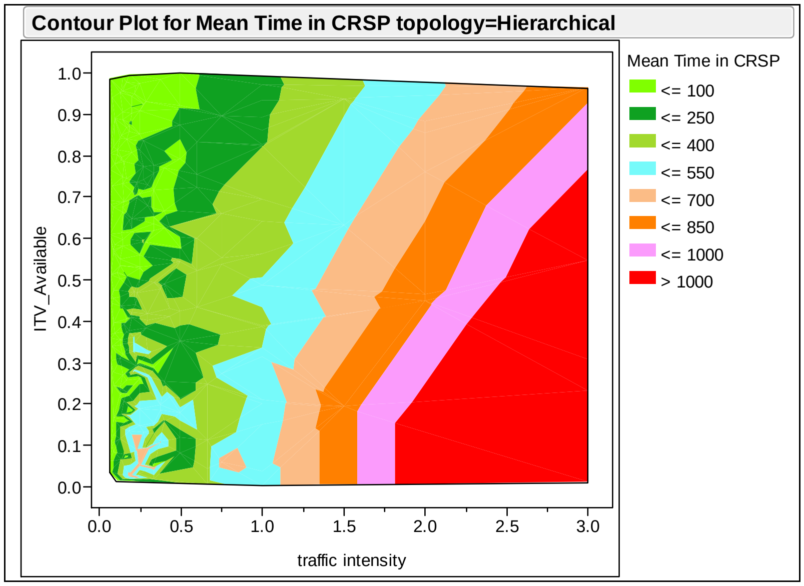
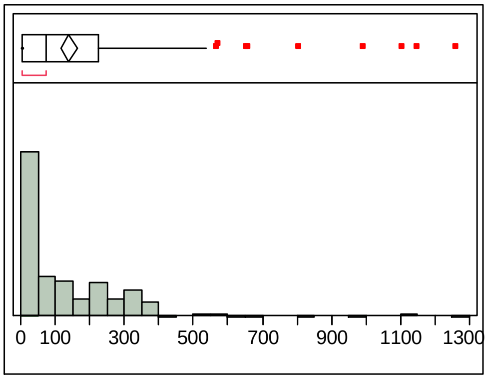


Figure 16. Contour Plot for Mean Time in CRSP, Hierarchical Network Structure (Best Viewed in Color)

2. Star Network Structure Velocity

The mean time in CRSP distribution plot and summary statistics for the 257 design points is shown in Figure 17. The results reveal that the mean time in CRSP for the Star network structure has a mean of 139.21 hours with a 95% confidence interval range from 115.73 hours to 162.69 hours. Analogous to the Hierarchical network structure, 13 data points with high mean time in CRSP result when the CRSP is highly congested with traffic intensity greater than 1.0. Nevertheless, a paired t-test shows that the mean time in CRSP for the Star network structure is significantly lower than that for the Hierarchical network structure (p-value < 0.0001) in the LBC model. To the extent that this adequately represents CRSP operations in theater, these results suggest that better mean time in CRSP is achieved with this network structure compared to the Hierarchical network structure.

Mean Time in CRSP



Quantiles

100.0%	maximum	1255.3
99.5%		1222.6
97.5%		650.9
90.0%		341.0
75.0%	quartile	223.7
50.0%	median	75.3
25.0%	quartile	4.9
10.0%		4.5
2.5%		4.2
0.5%		4.0
0.0%	minimum	4.0

Moments

Mean	139.20565
Std Dev	191.08238
Std Err Mean	11.919391
upper 95% Mean	162.67819
lower 95% Mean	115.7331
N	257

Figure 17. Distribution and Summary Statistics for Mean Time in CRSP, Star Network Structure

Figure 18 shows the regression tree for predicting the mean time in CRSP. It consists of six splits and achieves an R^2 value of 0.84. For the scenarios with traffic intensity greater than 1.0, it is evident that there is substantial queuing in the system and the best mean time in CRSP achieved is 538.63 hours. In contrast, with traffic intensity of 1.0 or less, the mean time in CRSP is better when the system is not congested; also, having ITV-Available of 0.242 or more improves the mean time in CRSP. Note that with low traffic intensity, the mean time in CRSP is 10.56 hours if ITV-Available is 0.242 or more, and 46.71 hours otherwise. On the other hand, when the system traffic intensity is 0.188 to less than 0.60 the time in CRSP improves from 103.97 hours to 71.16 hours with ITV-Available of 0.492 or more.

This regression tree behaves in a similar manner to that of the Hierarchical network structure regression tree. Likewise, the results from the regression tree reveal that traffic intensity and ITV-Available have the most influence on the mean time in CRSP.

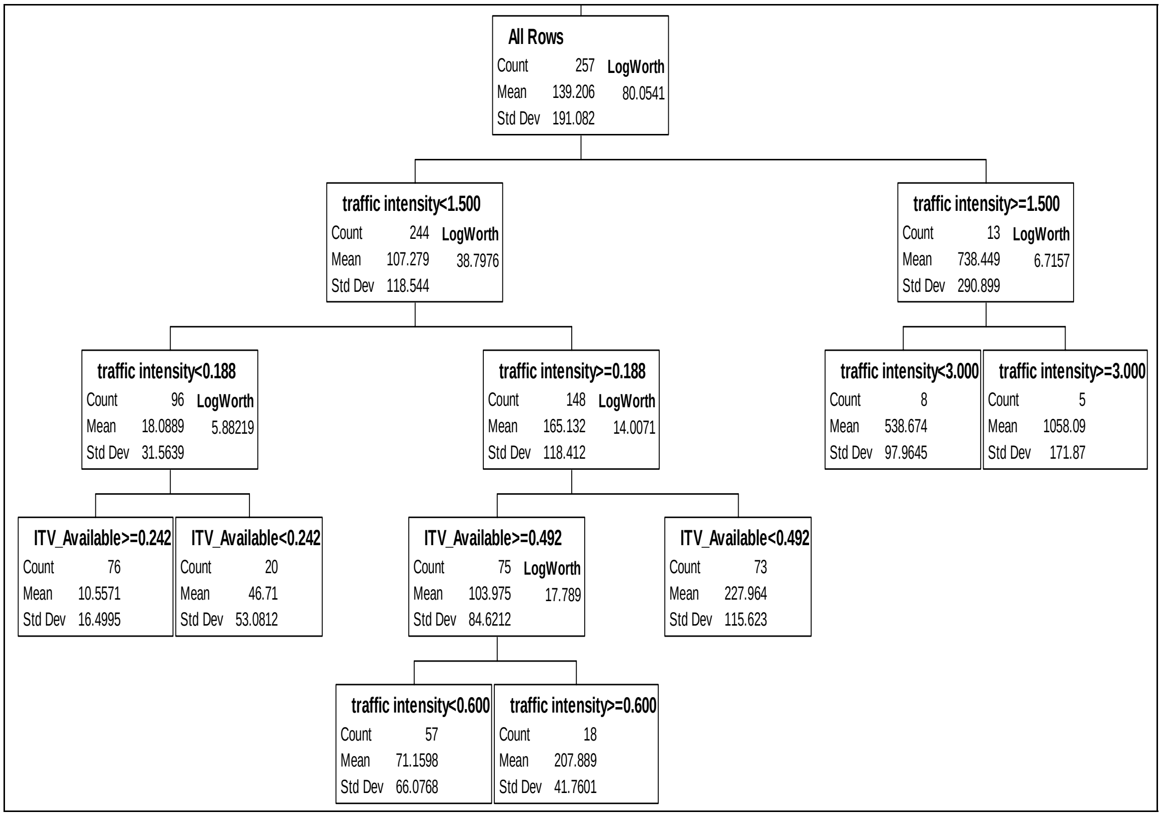


Figure 18. Regression Tree for Mean Time in CRSP, Star Network Structure

Figure 19 shows the final regression metamodel. The model yields an R^2 of 0.83 and contains four main effect terms and two interaction terms. Note that the model includes two terms (P[Comms] LCOP-Sup and Relay Pallet) which do affect the response significantly, but their interaction is significantly important. Similar to the Hierarchical network structure, the mean time in CRSP is influenced mainly by traffic intensity and ITV-Available, traffic intensity being the dominant factor. These results are considered acceptable based on the comparison to the results of a dissimilar DOE, using an analogous methodology to the Hierarchal network structure results. Moreover, these results serve to reinforce and complement those findings of the regression tree.

Whole Model

Summary of Fit

RSquare	0.829916
RSquare Adj	0.825834
Root Mean Square Error	79.74484
Mean of Response	139.2056
Observations (or Sum Wgts)	257

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	7757383.9	1292897	203.3101
Error	250	1589809.8	6359	**Prob > F**
C. Total	256	9347193.7		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	95.869685	13.99647	6.85	<.0001*
ITV_Available	-163.9666	17.28789	-9.48	<.0001*
P(Comms)_LCOP-Sup	-8.89931	17.29226	-0.51	0.6073
Relay_Pallet[0]	2.2483826	5.009382	0.45	0.6539
traffic intensity	317.508	9.691906	32.76	<.0001*
(ITV_Available-0.50222)*(traffic intensity-0.41024)	-88.9099	31.81349	-2.79	0.0056*
(P(Comms)_LCOP-Sup-0.50306)*Relay_Pallet[0]	79.159278	17.48618	4.53	<.0001*

Figure 19. Regression Metamodel for Mean Time in CRSP, Star Network Structure

The interaction plot in Figure 20 depicts the interaction term identified in the regression metamodel. These results are analogous to the Hierarchical network structure. In short, decreasing traffic intensity also decreases the mean time in CRSP. The decrease is larger when ITV-Available is low, but overall having ITV-Available high is better. Additionally, the interaction between P(Comms) LCOP-Sup and Relay Pallet indicates that the mean time in CRSP decreases as the probability of communications increases and the pallet lane has the capability to relay. At low probability of communications, the mean time in CRSP decreases when the pallet lane does not include the capability to relay.

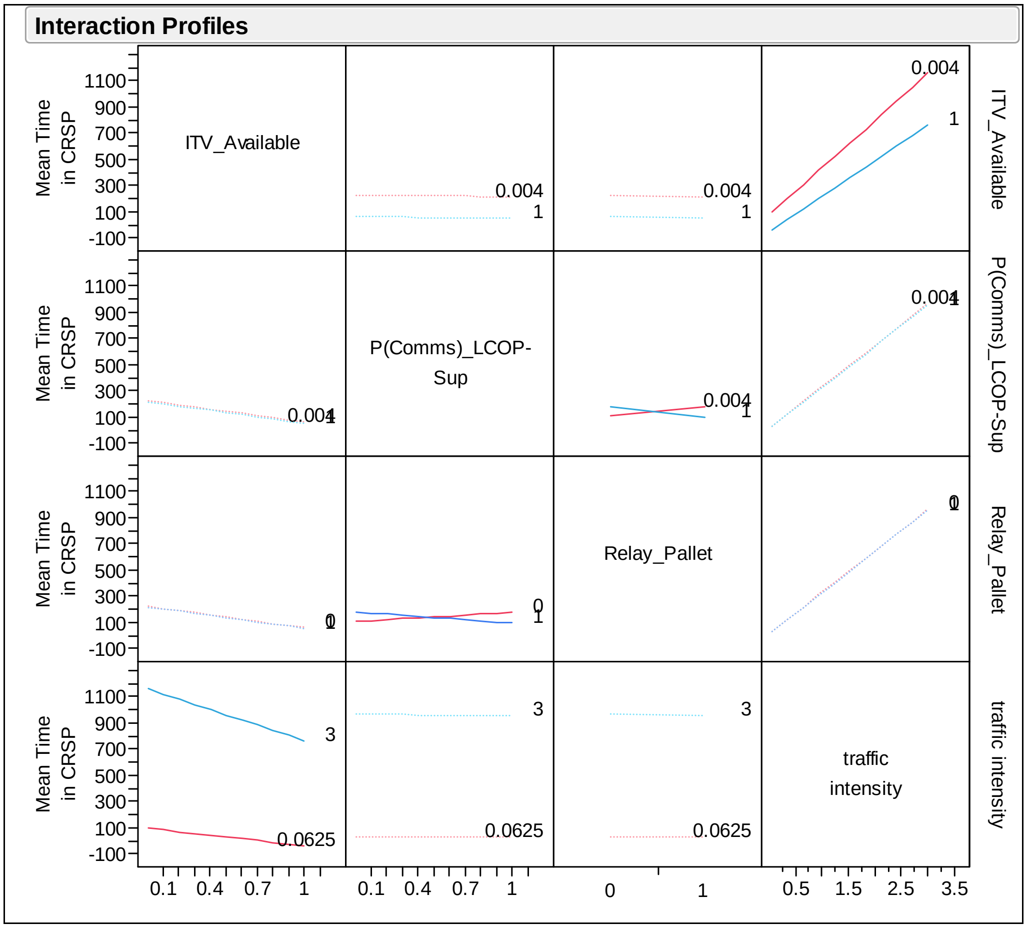


Figure 20. Interaction Profile Plot, Star Network Structure

Figure 21 shows the contour plot of ITV-Available by traffic intensity. This plot complements the metamodel and interaction plot results. For instance, with traffic intensity near 1.0 the mean time in CRSP is less than less than 250 hours with ITV-Available greater than 0.65. Contrarily, with ITV less than 0.65 the mean time in CRSP could be up to 400 hours as indicated by "islands" in the contour. Note that the contours' right motion or curvature is less noticeable compared to the previous network structure. Also, the filled contour corresponding to mean time in CRSP greater than 1000 hours is average in size compared to the others. This provides further insight into how the significant decrease in the mean time in CRSP, compared to the Hierarchical network structure, is achieved.

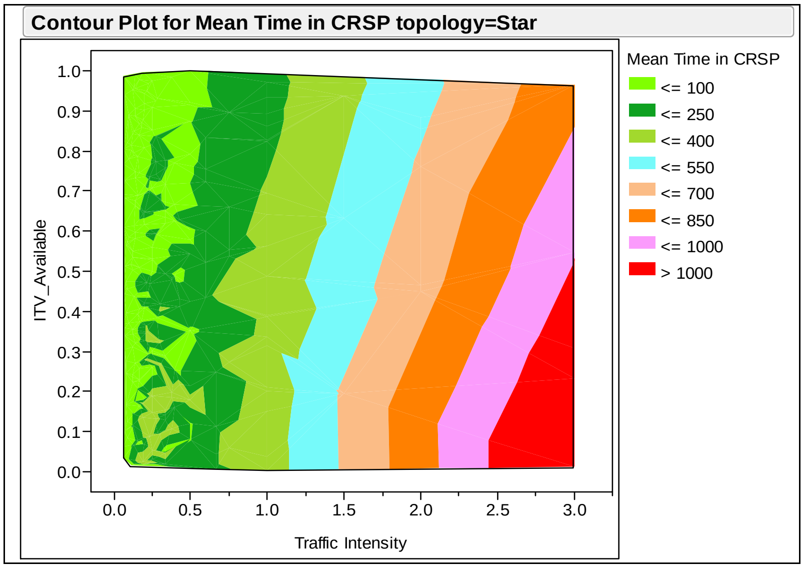


Figure 21. Contour Plot for Mean Time in CRSP, Star Network Structure (Best Viewed in Color)

3. Hierarchical-Star Network Structure Velocity

The mean time in CRSP distribution plot and summary statistics for the 257 design points is shown in Figure 22. The results reveal that the mean time in CRSP response variable has mean 119.32 hours with the 95% confidence interval range from 98.18 hours to 140.46 hours. This is significantly less than the mean time in CRSP for the Hierarchical and Star structures (p-values < 0.01). Analogous to the previous two network structures, 13 data points with high mean time in CRSP result when the CRSP is highly congested with traffic intensity greater than 1.0.

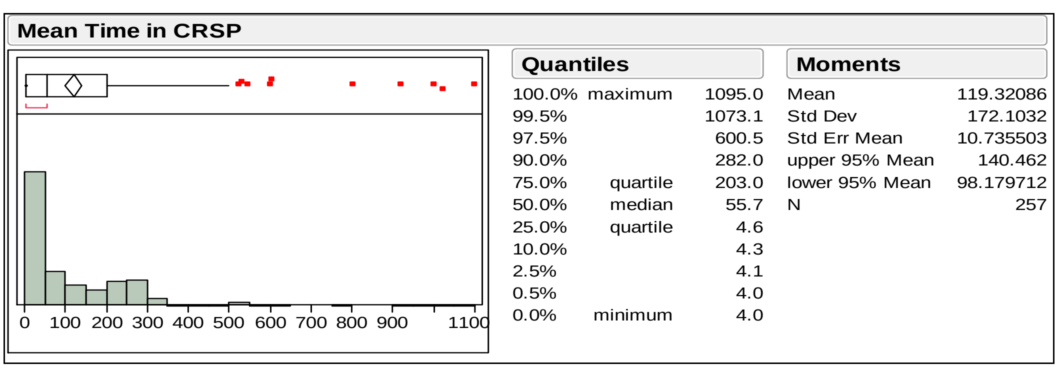


Figure 22. Distribution and Summary Statistics for Mean Time in CRSP, Hierarchical-Star Network Structure

Figure 23 shows the regression tree for predicting the mean time in CRSP. It consists of six splits and achieves an R^2 value of 0.87. For the scenarios with traffic intensity greater than 1.0, it is noticeable that there is substantial queuing in the system and the best mean time in CRSP achieved is 507.81 hours. In contrast, with traffic intensity of closer to zero, the mean time in CRSP is 19.72 hours (leftmost branch). On the other hand, when the system traffic intensity is 0.188 to less than 0.75, the time in CRSP improves from 118.08 hours to 69.00 hours with ITV-Available of 0.492 or more. This is much lower than the mean time in CRSP of 209.60 hours with traffic intensity of 0.75 to 1.0 (inclusive) and ITV-Available of 0.539 or greater.

Similar to the previous network structures, traffic intensity and ITV-Available have the greatest influence on the mean time in CRSP.

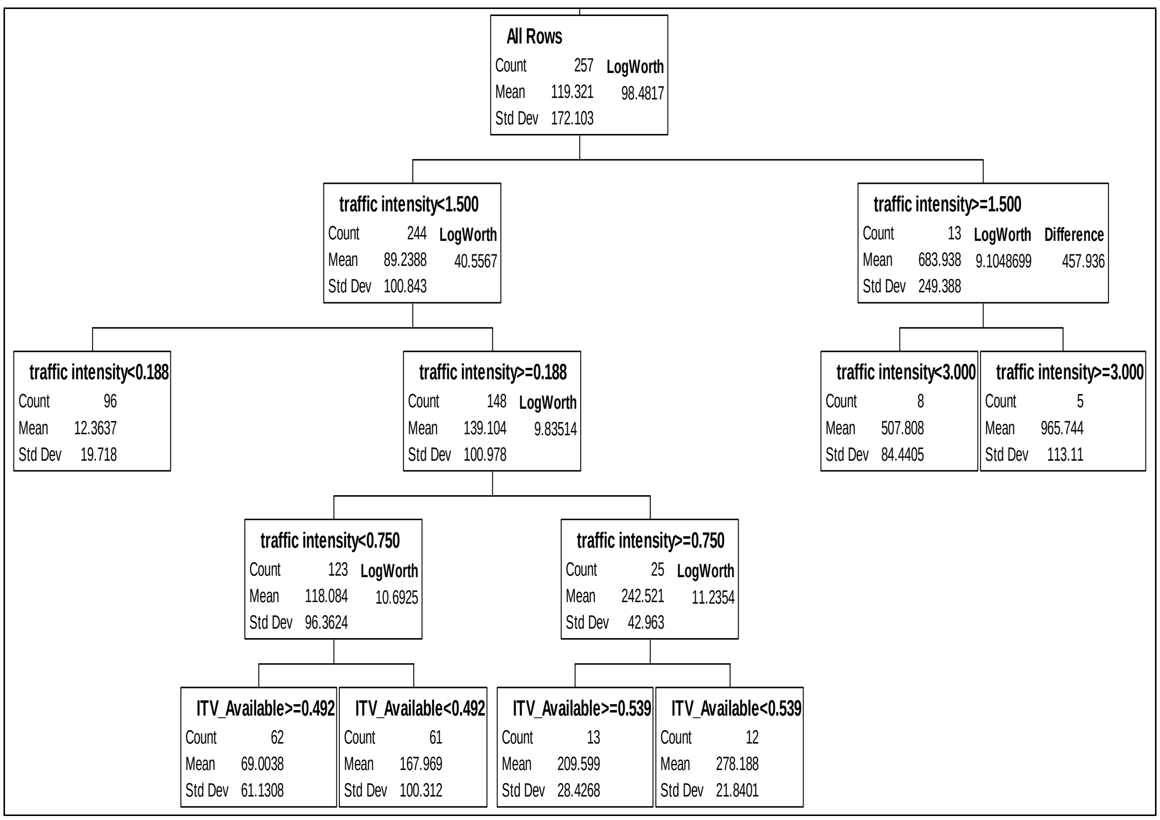


Figure 23. Regression Tree for Mean Time in CRSP, Hierarchical-Star Network Structure

Figure 24 shows the final regression metamodel. The model yields an R^2 of 0.86 and contains four main effect terms, two interaction terms, and one quadratic term. Similar to the previous two network structures, the mean time in CRSP is influenced mainly by traffic intensity and ITV-Available, traffic intensity being the dominant factor. Note that this metamodel includes two terms (P[Comms] Sup-Pal and Relay Cont) which do affect the response significantly, but their interaction is significantly important. Theses results emphasize the significance of network capability and the timely and reliable ITV data of cargo. These results are considered acceptable based on the comparison to the results of a dissimilar DOE, using an analogous methodology to the Hierarchal network structure results.

Whole Model

Summary of Fit

RSquare	0.859265
RSquare Adj	0.855308
Root Mean Square Error	65.4652
Mean of Response	119.3209
Observations (or Sum Wgts)	257

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	6515457.7	930780	217.1830
Error	249	1067137.4	4286	**Prob > F**
C. Total	256	7582595.1		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	61.679318	11.77262	5.24	<.0001*
ITV_Available	-119.0342	14.20757	-8.38	<.0001*
P(Comms)_Sup-Pal	11.301229	14.25498	0.79	0.4287
Relay_Cont[0]	5.8018451	4.095001	1.42	0.1578
traffic intensity	257.19944	15.97801	16.10	<.0001*
(ITV_Available-0.50222)*(P(Comms)_Sup-Pal-0.50298)	-149.8389	50.2786	-2.98	0.0032*
(P(Comms)_Sup-Pal-0.50298)*Relay_Cont[0]	72.523026	14.16316	5.12	<.0001*
(traffic intensity-0.41024)*(traffic intensity-0.41024)	23.54916	8.439649	2.79	0.0057*

Figure 24. Regression Metamodel for Mean Time in CRSP, Hierarchical-Star Network Structure

The interaction plot in Figure 25 depicts the two interaction terms identified in the regression metamodel. First, the interaction between ITV-Available and the P(Comms) Sup-Pal indicates that with ITV-Available at its high value, the mean time in CRSP decreases with higher probability of communications. However, if ITV-Available is 0.004, the mean time in CRSP increases as the probability of communications increases. Second, the interaction between P(Comms) Sup-Pal and Relay Cont indicates that the mean time in CRSP decreases as the probability of communications increases and the container lane has capability to relay. At low probability of communications, the mean time in CRSP decreases when the container lane does not include the communication relay capability.

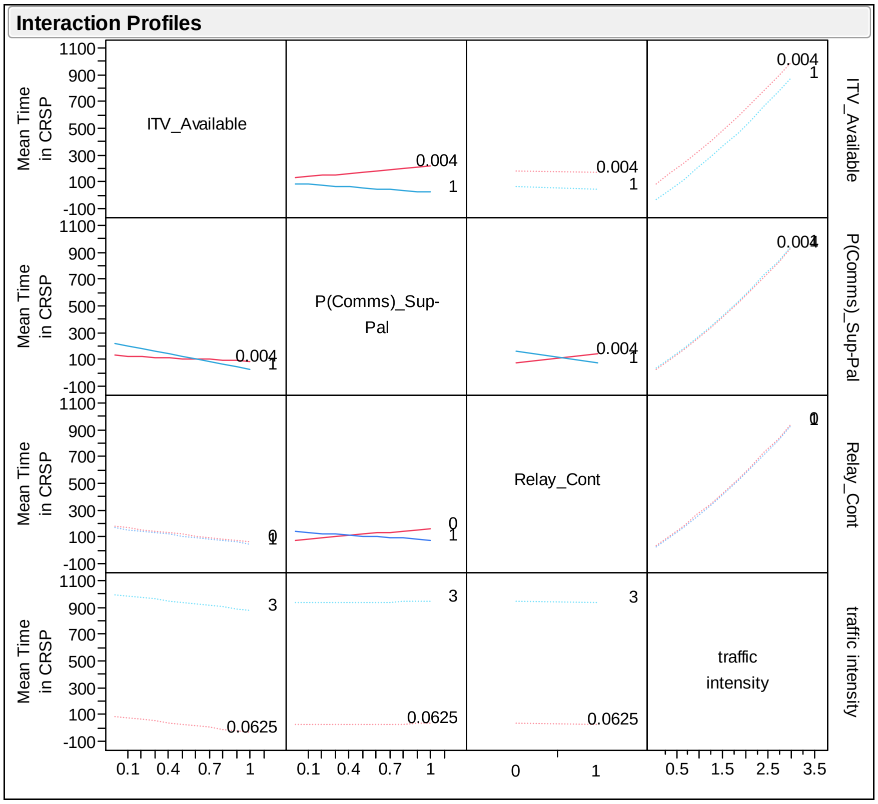


Figure 25. Interaction Profile Plot for Mean Time in CRSP, Hierarchical-Star Network Structure

Figure 26 shows the contour plot of ITV-Available by traffic intensity. This plot complements the metamodel and interaction plot results. Similar to the Star network structure, with traffic intensity near 1.0 the mean time in CRSP is less than less than 250 hours with ITV-Available greater than 0.55. Contrarily, with ITV-Available less than 0.55 the mean time in CRSP could be up to 400 hours as indicated by “islands” in the contour. Note that the contours’ right motion or curvature is less that the previous two networks. Also, the filled contour corresponding to mean time in CRSP greater than 1000 hours is smaller in size compared to the previous contour plots. Comparing all three contour plots provides more insight into how this network structure performs better than the previous two networks.

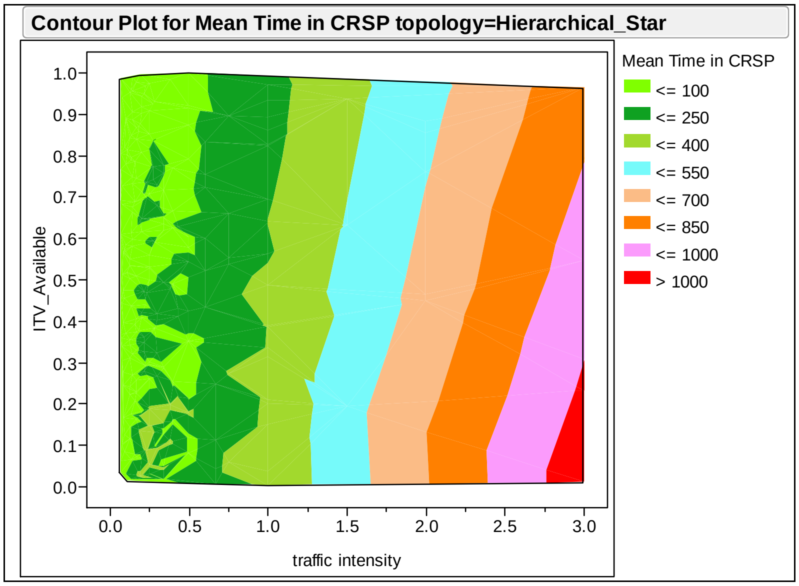


Figure 26. Contour Plot for Mean Time in CRSP, Hierarchical-Star Network Structure (Best Viewed in Color)

4. Hierarchical Network Structure Reliability

To understand the reliability of the of the Hierarchical network structure, the variability of the mean time in CRSP is explored. As a practical matter, a variability chart of the 257 design points categorized by traffic intensity is shown in Figure 27. The bars represent the 95% confidence interval by traffic intensity. The blue line connecting the bars corresponds to the mean time in CRSP, and the value at the right of the chart is the mean of the 257 design points. The results indicate that the mean time in CRSP is prone to a great deal of variability, even with traffic intensity less than 1.0. Evidently, with the Hierarchical network structure in place, the CRSP is capable of handling the traffic intensity but with poor velocity.

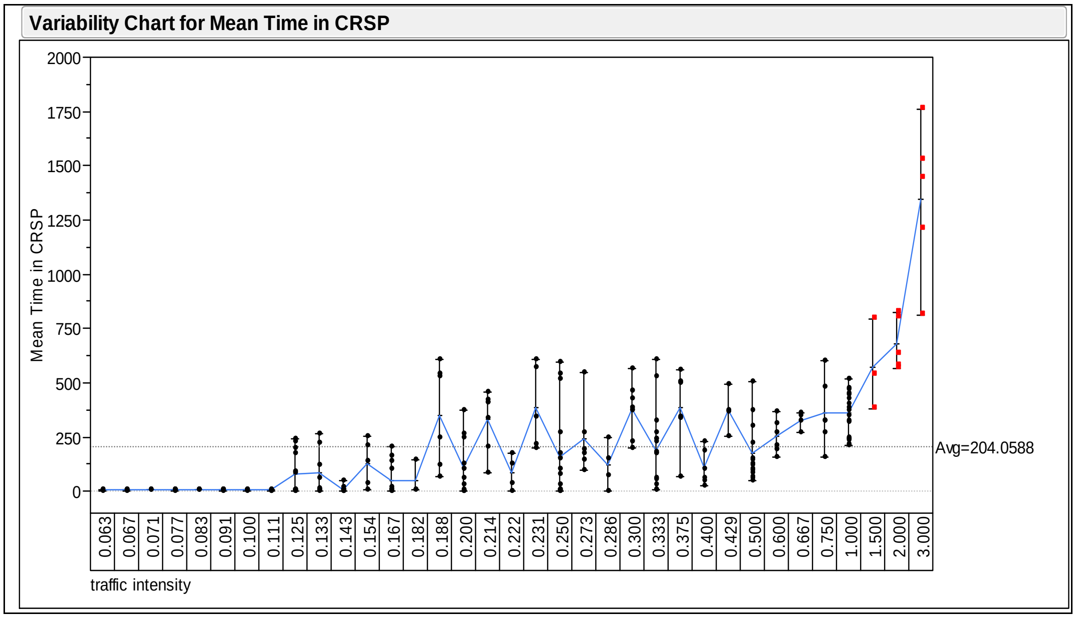


Figure 27. Variability Plot for Mean Time in CRSP by Traffic Intensity, Hierarchical Network Structure

5. Star Network Structure Reliability

Figure 28 shows the plot for the variability of the mean time in CRSP for the 257 design points categorized by traffic intensity. The results indicate that the mean time in CRSP is less prone to variability; hence the Star network structure is more reliable than the Hierarchical network structure. Accordingly, with the Star network structure in place the CRSP is capable of handling the traffic intensity but with better velocity and reliability than the previous case.

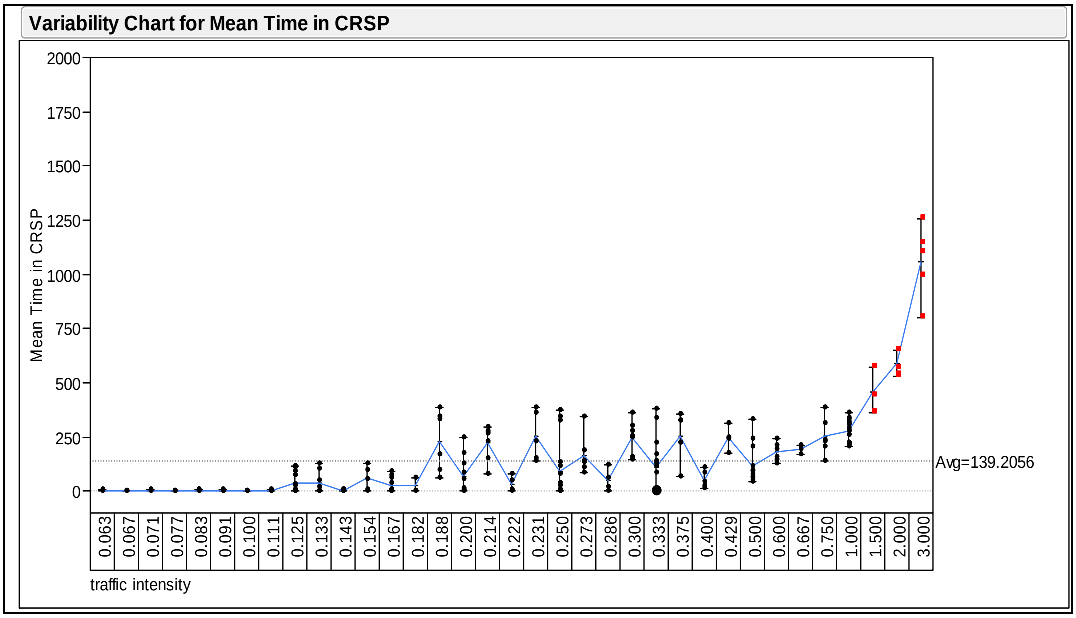


Figure 28. Variability Plot for Mean Time in CRSP by Traffic Intensity, Star Network Structure

6. Hierarchical-Star Network Structure Reliability

Figure 29 shows the plot for the variability of the mean time in CRSP for the 257 design points categorized by traffic intensity. Once again, the results indicate that the mean time in CRSP variability is consistently more stable with less variability than the previous two networks, thus more reliable. Given these facts, with the Hierarchical-Star network structure in place the CRSP still has difficulty handling high traffic intensity, but is able to achieve both a lower mean and better velocity and reliability

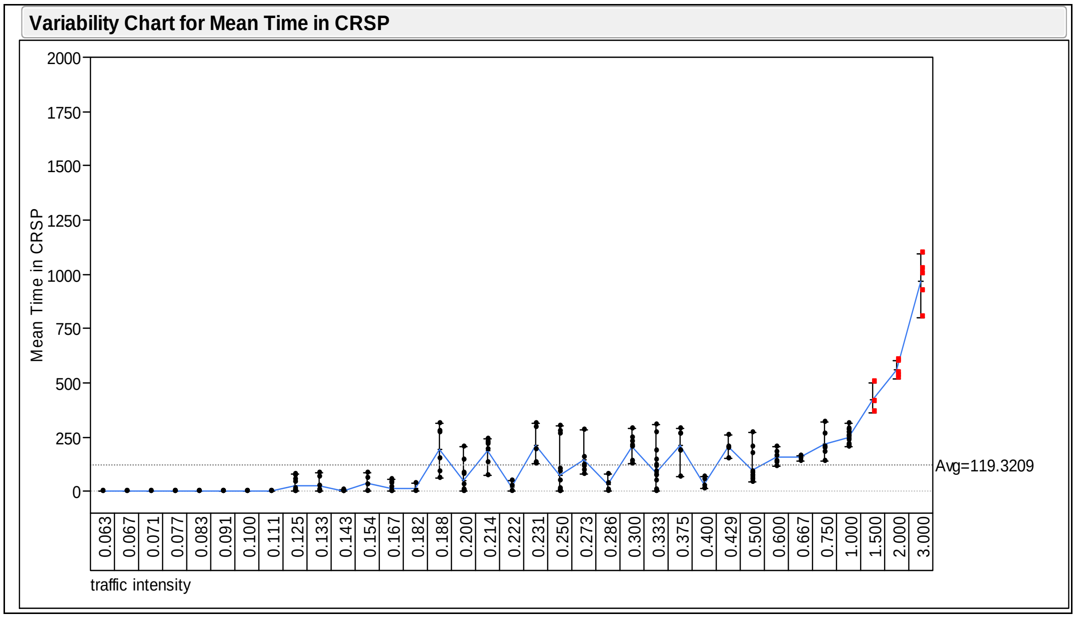
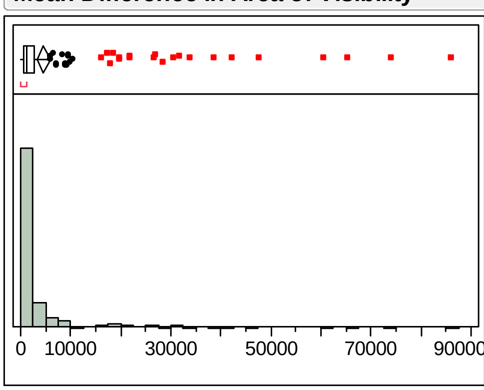


Figure 29. Variability Plot for Mean Time in CRSP by Traffic Intensity, Hierarchical-Star Network Structure

7. Hierarchical Network Structure Visibility

The mean difference in area of visibility distribution plot and summary statistics for the 257 design points is shown in Figure 30. The results reveal that the mean difference in area of visibility has a mean of 4518.60 with a 95% confidence interval range from 3172.46 to 5864.73.

Mean Difference in Area of Visibility



Quantiles

100.0%	maximum	85861
99.5%		82362
97.5%		40296
90.0%		9462
75.0%	quartile	2616
50.0%	median	1225
25.0%	quartile	617
10.0%		341
2.5%		120
0.5%		45
0.0%	minimum	41

Moments

Mean	4518.5917
Std Dev	10958.46
Std Err Mean	683.56997
upper 95% Mean	5864.7282
lower 95% Mean	3172.4552
N	257

Figure 30. Distribution and Summary Statistics for Mean Difference in Area of Visibility, Hierarchical Network Structure

Figure 31 shows the regression tree for predicting the mean difference in area of visibility. The regression tree consists of six splits and achieves an R^2 value of 0.46. The first split at the top indicates that better mean difference in area is attained for the 252 scenarios with P(Comms) Sup-Cont equal to or greater than 0.023, compared to the 5 scenarios with P(Comms) Sup-Cont less than 0.023. The subsequent five splits explore the scenarios with P(Comms) Sup-Cont equal to or greater than 0.023. The leftmost branch indicates that when the Relay Sup is zero (communications relay capability not available) the mean difference in area is better when the LCOP-Update is less than 0.199. On the other hand, for the scenarios where the Relay Sup is one (communications relay capability available) the mean difference in area is better when the P(Comms) LCOP-Sup is equal to or greater than 0.066. Plus it improves when P(Comms) Sup-Pal is 0.047 or greater.

Recall that in the Hierarchical network topology the supervisor lane is connected to the LCOP, and the remaining lanes are connected to the supervisor in a hierarchical manner. The regression tree results indicate that the mean difference in area of visibility is better with higher probability of communications and when the supervisor lane is able to relay information. Explicitly, better mean difference in area of visibility is achieved with the supervisor relay capability available given connectivity among the communications channels. On the other hand, if the supervisor relay capability is not available, the mean difference in area of visibility improves when the LCOP Update rate is less than 0.199 hours.

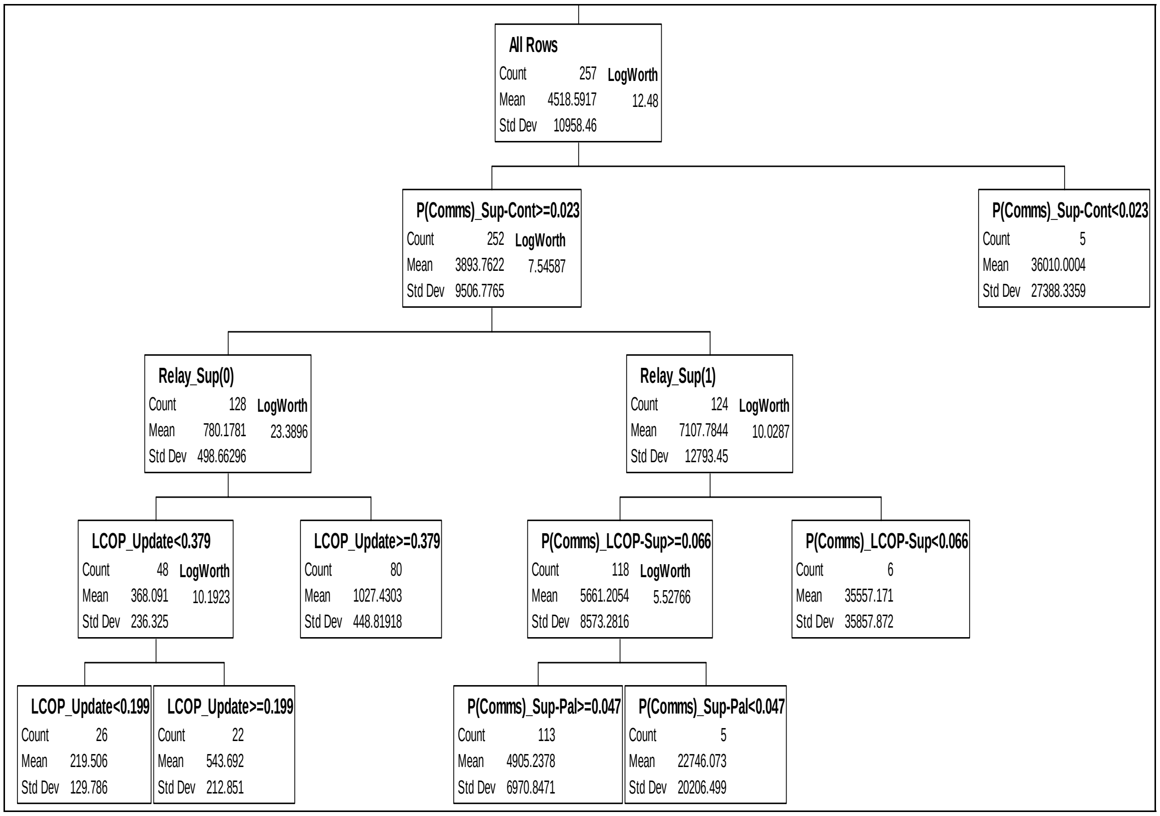


Figure 31. Regression Tree for Mean Difference in Area of Visibility, Hierarchical Network Structure

The metamodel for this experiment is shown in Figure 32. The model yields an R^2 of 0.40 and contains eight main effect terms, six interaction terms, and one quadratic term. The regression metamodel findings go together with those of the regression tree. As expected, the most dominant factors are the LCOP-Sup probability of communications and the communications relay capability of the supervisor lane. This model implies that the mean difference in area of visibility is influenced primarily on the connectivity between the LCOP and the supervisor lane. Additionally, the mean difference in area of visibility depends on the connectivity between the supervisor lane and both the pallet and rolling stock lanes.

Response Visibility topology=Hierarchical

Summary of Fit

RSquare	0.40343
RSquare Adj	0.366299
Root Mean Square Error	8723.522
Mean of Response	4518.592
Observations (or Sum Wgts)	257

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	15	1.2402e+10	826828617	10.8651
Error	241	1.834e+10	76099838	**Prob > F**
C. Total	256	3.0742e+10		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	14357.311	2301.487	6.24	<.0001*
ITV_Available	-4115.893	1894.713	-2.17	0.0308*
P(Comms)_LCOP-Sup	-8448.746	1892.751	-4.46	<.0001*
P(Comms)_Sup-RS	-5033.203	1900.179	-2.65	0.0086*
P(Comms)_Sup-Pal	-5245.277	1884.544	-2.78	0.0058*
P(Comms)_Sup-Cont	-2340.684	1893.12	-1.24	0.2175
Convoy_Case{1&2-3}	-32.80615	581.6823	-0.06	0.9551
Relay_Sup[0]	-4036.079	548.8339	-7.35	<.0001*
Relay_Pallet[0]	-696.9802	546.6539	-1.27	0.2035
(ITV_Available-0.50265)*Relay_Pallet[0]	4884.4144	1906.855	2.56	0.0110*
(P(Comms)_LCOP-Sup-0.50261)*(Convoy_Case{1&2-3}-0.33852)	-6868.391	2043.72	-3.36	0.0009*
(P(Comms)_LCOP-Sup-0.50261)*Relay_Sup[0]	9801.6984	1917.721	5.11	<.0001*
(P(Comms)_Sup-RS-0.5025)*Relay_Sup[0]	4334.8795	1905.964	2.27	0.0238*
(P(Comms)_Sup-Pal-0.50369)*Relay_Sup[0]	4952.6533	1893.574	2.62	0.0095*
(P(Comms)_Sup-Cont-0.50306)*(Convoy_Case{1&2-3}-0.33852)	4370.3812	2043.546	2.14	0.0335*
(P(Comms)_LCOP-Sup-0.50261)*(P(Comms)_LCOP-Sup-0.50261)	35762.652	7516.571	4.76	<.0001*

Figure 32. Regression Metamodel for Mean Difference in Area of Visibility, Hierarchical Network Structure

The interaction plot in Figure 33 depicts the interaction terms identified in the regression metamodel. First, the interaction between ITV-Available and Relay Pallet indicates that if ITV-Available is at its highest value, the mean difference in area of visibility decreases with communications relay capability available. However, with ITV-Available at its lowest value (near zero), the mean time in CRSP increases with the communications relay capability. Note that the mean difference in area of visibility is nearly equal without the communications relay capability, regardless of the ITV-Available value level. Second, Relay Sup has interaction with three other terms, namely P(Comms) LCOP-Sup, P(Comms) Sup-RS, and P(Comms) Sup-Pal. The mean difference in area of visibility decreases with high probability of communications for LCOP-Sup, Sup-RS, and Sup-Pal respectively, regardless of the relaying capability.

Third, Convoy Case interacts with P(Comms) LCOP-Sup and P(Comms) Sup-Cont. The mean difference in area of visibility slightly decreases for convoy case one and two given Sup-Cont high probability of communications.

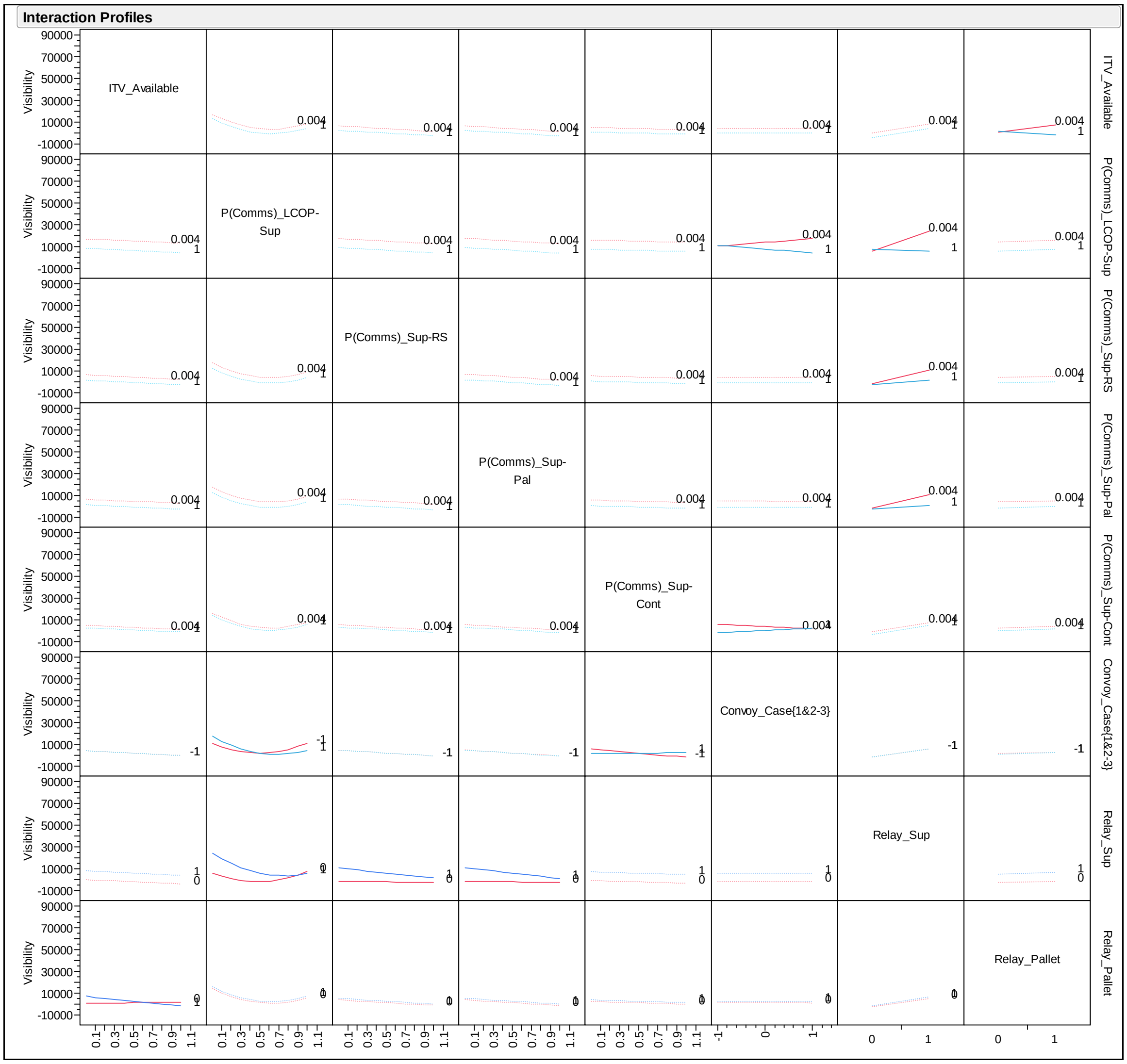


Figure 33. Interaction Profile Plot for Mean Difference Area of Visibility, Hierarchical Network Structure

Figure 34 shows the plot for the variability of the mean difference in area of visibility for the 257 design points categorized by traffic intensity. An examination of the data exposed 21 data points with extremely high values (greater than 10,000). Further investigation revealed that these observations result when the CRSP is processing two or more convoys per hour but are not those with the highest traffic intensities.

Unsurprisingly, the chart points out that the mean difference in area of visibility is prone to a great deal of variability. Certainly, these results substantiate the aforementioned findings regarding the network-enabled capabilities provided by the Hierarchical network structure.

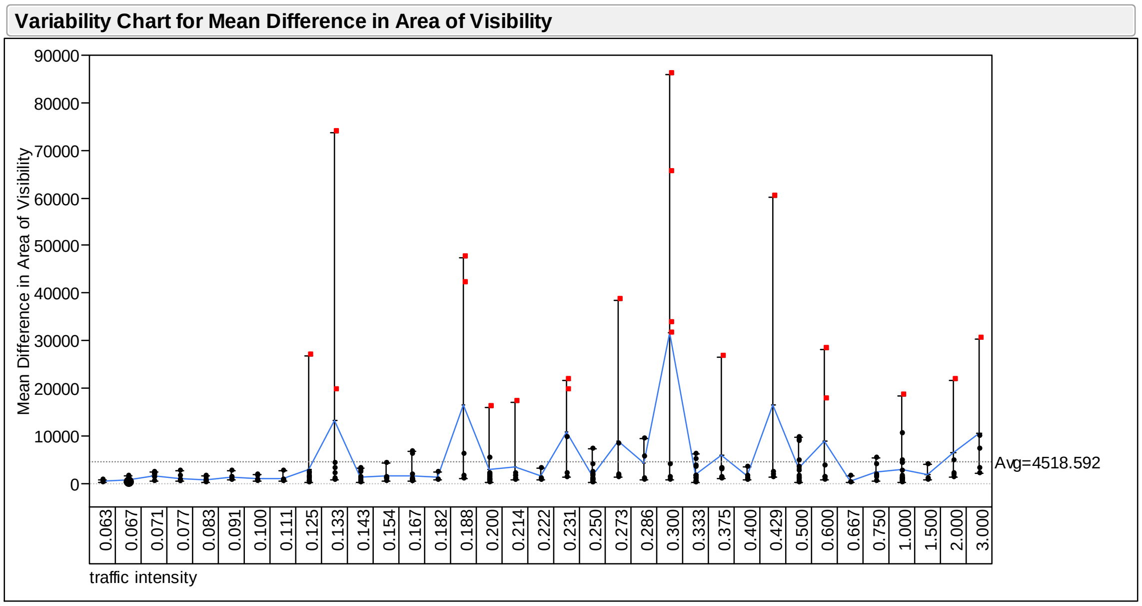
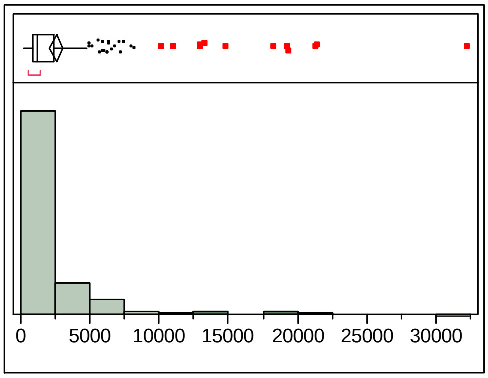


Figure 34. Variability Chart for Mean Difference in Area of Visibility, Hierarchical Network Structure

8. Star Network Structure Visibility

The mean difference in area of visibility distribution plot and summary statistics for 257 design points is shown in Figure 35. The results reveal that the overall mean is 2546.80 with a 95% confidence interval range from 2071.64 to 3021.95 hours. Seven data points have extremely high values (greater than 10,000), which result when the CRSP is processing two or more convoys per hour. This is only 1/3 the number of points for the Hierarchical network structure, and a paired t-test shows the overall mean for the Star network structure is significantly less than that of the Hierarchical network structure (p-value < 0.0001).

Mean Difference in Area of Visibility



Quantiles

100.0%	maximum	32232
99.5%		29117
97.5%		16755
90.0%		5949
75.0%	quartile	2424
50.0%	median	1242
25.0%	quartile	819
10.0%		547
2.5%		318
0.5%		189
0.0%	minimum	182

Moments

Mean	2546.7962
Std Dev	3868.0821
Std Err Mean	241.28433
upper 95% Mean	3021.9511
lower 95% Mean	2071.6412
N	257

Figure 35. Distribution and Summary Statistics for Mean Difference in Area of Visibility, Star Network Structure

Figure 36 shows the regression tree for predicting the mean difference in area of visibility. It consists of five splits and achieves an R^2 value of 0.56. Looking at all of the splits, it is evident that the mean difference in area of visibility is better when the probability of communications exist between the LCOP and CRSP lanes, specifically the LCOP-Cont, the LCOP-Pal, and the LCOP-RS. Recall that in the Star network structure, all of the CRSP lanes are connected directly to the LCOP. The regression tree results indicate that the mean difference in area of visibility is better with higher probability of communications regardless of the relay capability. This indicates that better visibility is achieved when the lanes have direct connectivity with the LCOP bypassing the supervisor lane.

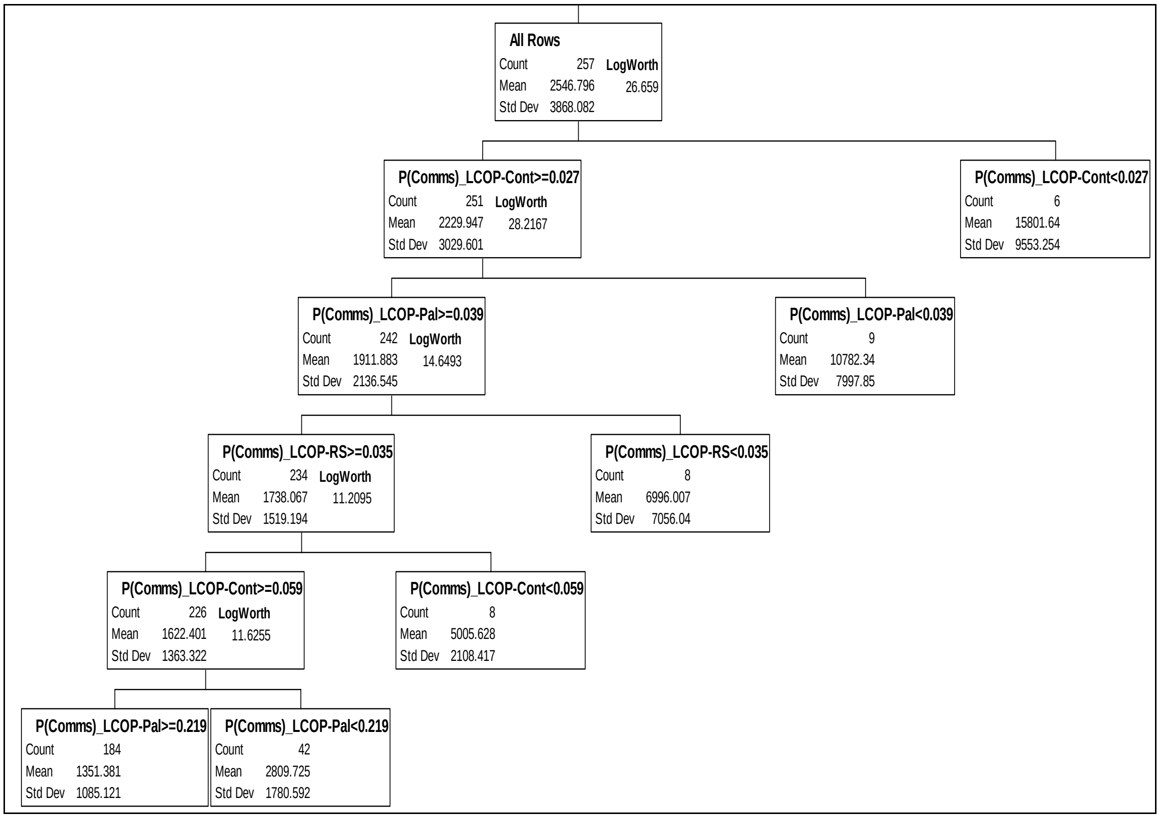


Figure 36. Regression Tree for Mean Difference in Area of Visibility, Star Network Structure

The final metamodel for this experiment is shown in Figure 37. The model yields an R^2 of 0.34 and contains six main effect terms, two interaction terms, and three quadratic terms. As anticipated, the regression metamodel findings complement those of the regression tree. The most significant factors are the probability of communications for all of the CRSP lanes (but the supervisor lane), the availability of the information regarding the cargo, and the LCOP-Update rate. This model explains the complexity of this network structure. It suggests that the mean difference in area of visibility depends on reliable connectivity between the pallet, container, and rolling stock lanes with the LCOP. Furthermore, it suggests that the mean difference in area of visibility is affected by the timely access of the information regarding the cargo and the frequency at which the LCOP is updated with such information.

Response Mean Difference in Area of Visibility

Summary of Fit

RSquare	0.340551
RSquare Adj	0.310943
Root Mean Square Error	3210.875
Mean of Response	2546.796
Observations (or Sum Wgts)	257

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	11	1304406926	118582448	11.5020
Error	245	2525880236	10309715	**Prob > F**
C. Total	256	3830287161		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4808.8673	913.1189	5.27	<.0001*
ITV_Available	-2286.49	695.7523	-3.29	0.0012*
LCOP_Update	1887.3978	691.7193	2.73	0.0068*
P(Comms)_LCOP-RS	-1882.611	691.7951	-2.72	0.0070*
P(Comms)_LCOP-Pal	-3744.915	695.3582	-5.39	<.0001*
P(Comms)_LCOP-Cont	-3071.642	692.8056	-4.43	<.0001*
Relay_Cont[0]	60.799175	200.6886	0.30	0.7622
(LCOP_Update-0.50002)*(P(Comms)_LCOP-Pal-0.5025)	-7100.329	2266.044	-3.13	0.0019*
(P(Comms)_LCOP-Cont-0.50369)*Relay_Cont[0]	-1900.393	701.6126	-2.71	0.0072*
(P(Comms)_LCOP-RS-0.50002)*(P(Comms)_LCOP-RS-0.50002)	7195.9882	2726.41	2.64	0.0088*
(P(Comms)_LCOP-Pal-0.5025)*(P(Comms)_LCOP-Pal-0.5025)	9186.194	2706.585	3.39	0.0008*
(P(Comms)_LCOP-Cont-0.50369)*(P(Comms)_LCOP-Cont-0.50369)	11131.417	2777.312	4.01	<.0001*

Figure 37. Regression Metamodel for Mean Difference in Area of Visibility, Star Network Structure

The interaction plot in Figure 38 depicts the two interaction terms identified in the regression metamodel. First, the interaction between P(Comms) LCOP-Pal and LCOP-Update imply that given a low LCOP-Pal probability of communications, the mean difference in area of visibility is mitigated with frequent LCOP updates. The second interaction is between P(Comms) LCOP-Cont and Relay Cont. The mean difference in area of visibility is mitigated with communications relay capability, given low probability of communications. Conversely, without the communications relay capability, the mean difference in area decreases with high probability of communications.

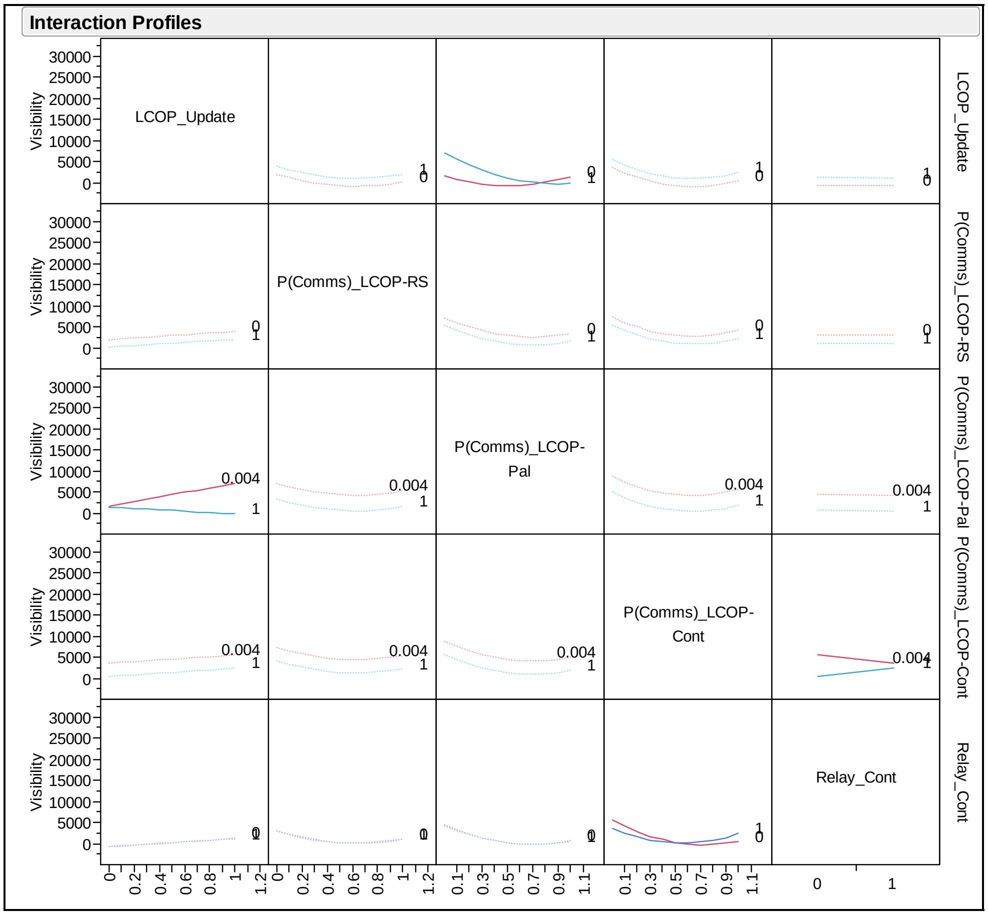


Figure 38. Interaction Profile Plot for Mean Difference in Area of Visibility, Star Network Structure

Figure 49 shows the plot for the variability of the mean difference in area of visibility for the 257 design points categorized by traffic intensity. The chart points out that the mean difference in area of visibility is less prone to variability. These results substantiate the aforementioned findings regarding the network-enabled capabilities provided by the Star network structure, such as greater visibility achieved improving cargo operations and velocity management.

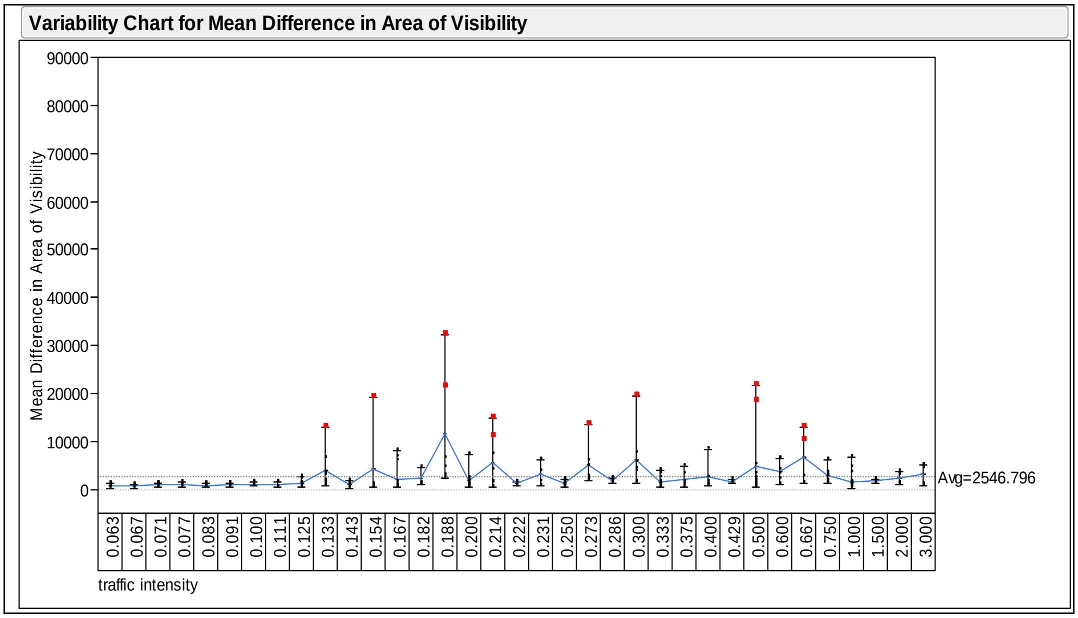
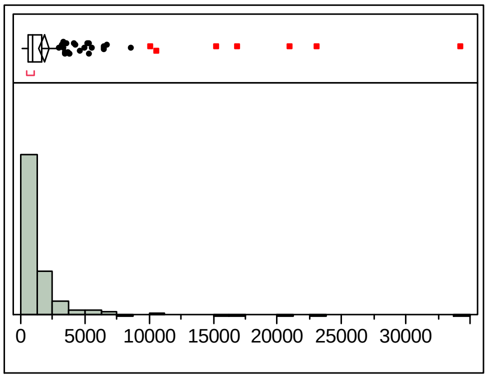


Figure 39. Variability Plot for Mean Difference in Area of Visibility, Star Network Structure

9. Hierarchical-Star Network Structure Visibility

The mean difference in area of visibility distribution plot and summary statistics for the 257 design points is shown in Figure 40. The results reveal that the overall mean is 1837.17 with a 95% confidence interval range from 1425.60 to 2248.74 hours. Analogous to the Star network structure, seven data points have extremely high values (greater than 10,000), which result when the CRSP is processing two or more convoys per hour. . The overall mean for the Hierarchical-Star network structure is significantly less than that of the both Hierarchical and Star network structure (p-values < 0.01).

Mean Difference in Area of Visibility



Quantiles

100.0%	maximum	34146
99.5%		30897
97.5%		10282
90.0%		3526
75.0%	quartile	1578
50.0%	median	972
25.0%	quartile	631
10.0%		447
2.5%		256
0.5%		159
0.0%	minimum	150

Moments

Mean	1837.1668
Std Dev	3350.4571
Std Err Mean	208.99577
upper 95% Mean	2248.7367
lower 95% Mean	1425.5969
N	257

Figure 40. Distribution and Summary Statistics for Mean Difference in Area of Visibility, Hierarchical-Star Network Structure

Figure 41 shows the regression tree for predicting the mean difference in area of visibility for the Hierarchical-Star network structure. It consists of five splits and achieves an R^2 value of 0.47. Recall that in the Hierarchical-Star network structure all of the CRSP lanes are connected directly to the supervisor lanes, as well as connected to the LCOP. Looking at all of the splits, it is evident that the mean difference in area is better when higher probability of communications exist between the LCOP and CRSP lanes, specifically the LCOP-Cont, the LCOP-Pal, and the LCOP-RS. This behavior is analogous to the Star network structure regression tree where better visibility is achieved when the lanes communicate directly with the LCOP, bypassing the supervisor. On the other hand, with lower probability of communications, the mean difference in area of visibility improves with the supervisor relay capability.

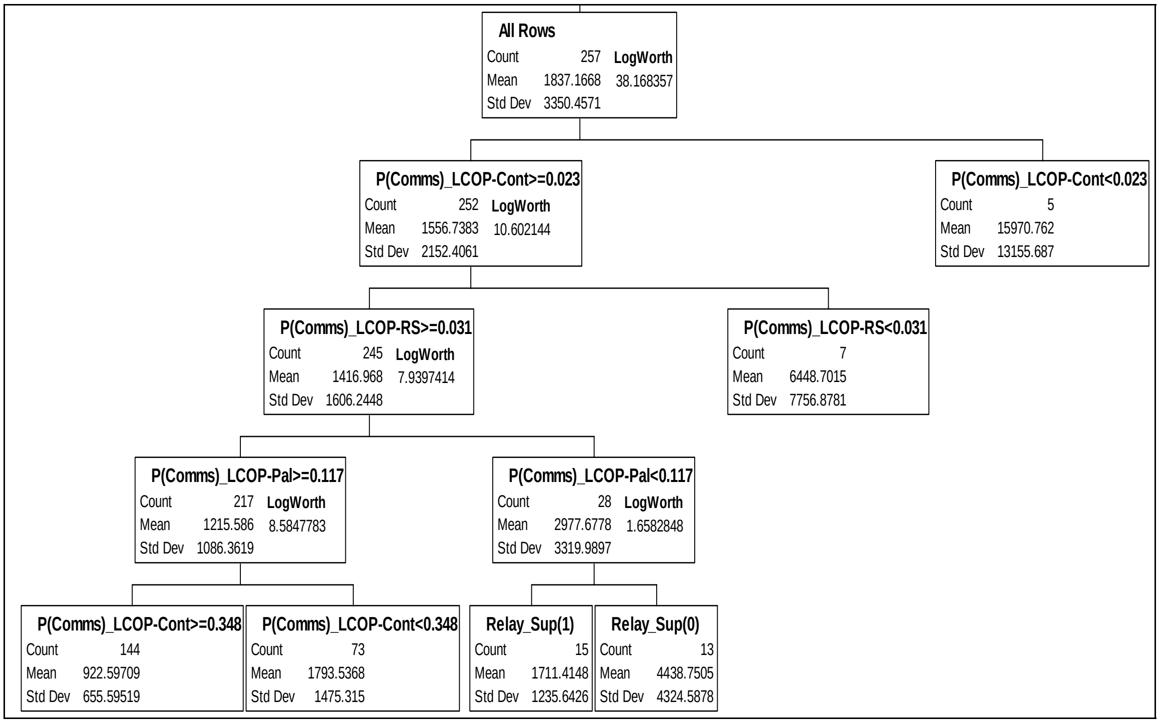


Figure 41. Regression Tree for Mean Difference in Area of Visibility, Hierarchical-Star Network Structure

The final metamodel for this experiment is shown in Figure 42. The model yields an R^2 of 0.36 and contains eight main effect terms, five interaction terms, and two quadratic terms. The most significant factors are the supervisor lane capability to relay , the LCOP-Cont, the LCOP-Pal, and the LCOP-RS probability of communications, LCOP-Update, and ITV-Available. Interestingly, the model provides more insight regarding ITV-Accuracy, a term not identified by the previous two network structures. This model explains the complexity of this network structure. It suggests that the mean difference in area of visibility depends on reliable connectivity between the pallet, container, and rolling stock lanes with the LCOP. When the connectivity is not as reliable the network relies on the supervisor and pallet lane communications relay capability. Furthermore, it suggests that the mean difference in area of visibility is affected by the timely access of accurate information regarding the cargo and the frequency at which the LCOP is updated with such information.

Response Visibility topology=Hierarchical_Star

Summary of Fit

RSquare	0.355198
RSquare Adj	0.315066
Root Mean Square Error	2772.864
Mean of Response	1837.167
Observations (or Sum Wgts)	257

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	15	1020749598	68049973	8.8506
Error	241	1852994551	7688774.1	**Prob > F**
C. Total	256	2873744149		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3140.4157	818.9135	3.83	0.0002*
ITV_Available	-1202.136	604.0936	-1.99	0.0477*
ITV_Accuracy	1274.4494	600.5938	2.12	0.0349*
LCOP_Update	1244.6421	599.6039	2.08	0.0390*
P(Comms)_LCOP-RS	-1054.021	599.8951	-1.76	0.0802
P(Comms)_LCOP-Pal	-2325.033	603.178	-3.85	0.0001*
P(Comms)_LCOP-Cont	-2769.146	598.9156	-4.62	<.0001*
Relay_Sup[0]	847.27058	173.6812	4.88	<.0001*
Relay_Pallet[0]	-94.39672	175.0624	-0.54	0.5902
(LCOP_Update-0.50002)*(P(Comms)_LCOP-Pal-0.5025)	-5708.352	2005.805	-2.85	0.0048*
(P(Comms)_LCOP-RS-0.50339)*Relay_Pallet[0]	1785.8547	610.6559	2.92	0.0038*
(P(Comms)_LCOP-Pal-0.5025)*Relay_Sup[0]	-1803.08	620.3118	-2.91	0.0040*
(P(Comms)_LCOP-Cont-0.50369)*Relay_Sup[0]	-2189.415	607.9276	-3.60	0.0004*
(P(Comms)_LCOP-RS-0.50339)*(P(Comms)_LCOP-RS-0.50339)	5636.3994	2433.675	2.32	0.0214*
(ITV_Accuracy-0.50265)*(P(Comms)_LCOP-Cont-0.50369)	-5043.093	2175.77	-2.32	0.0213*
(P(Comms)_LCOP-Cont-0.50369)*(P(Comms)_LCOP-Cont-0.50369)	8600.0578	2389.683	3.60	0.0004*

Figure 42. Regression Metamodel for Mean Difference in Area of Visibility, Hierarchical-Star Network Structure

The interaction plot in Figure 43 depicts the interaction terms identified in the regression metamodel. First, the interactions between P(Comms) LCOP-Cont and Relay Sup, as well as P(Comms) LCOP-Pal and Relay Sup, have similar behavior. Given low probability of communications, the mean difference in area of visibility is mitigated with the capability to relay. With high probability of communications, the mean difference in area of visibility is not affected by the capability to relay. Second, the interaction between P(Comms) LCOP-RS and Relay Pallet displays opposite behavior to the previous interactions discussed. Given high probability of communications, the mean difference in area of visibility decreases with the capability to relay. With low probability of communications, the mean difference in area of visibility decreases without the relay capability. Third, there is an interaction between LCOP-Update and P(Comms) LCOP-Pal. Once again, given a low LCOP-Pal probability of communications, the mean difference in area of visibility is mitigated with frequent LCOP updates. Last, the interaction between ITV-Accuracy and P(Comms) LCOP-Cont shows that given low ITV-Accuracy, the mean difference in area of visibility decreases as the probability of communications increases but at high probability of communications it starts increasing. With high ITV-Accuracy, the mean difference in area of visibility decreases as the probability of communications increases.

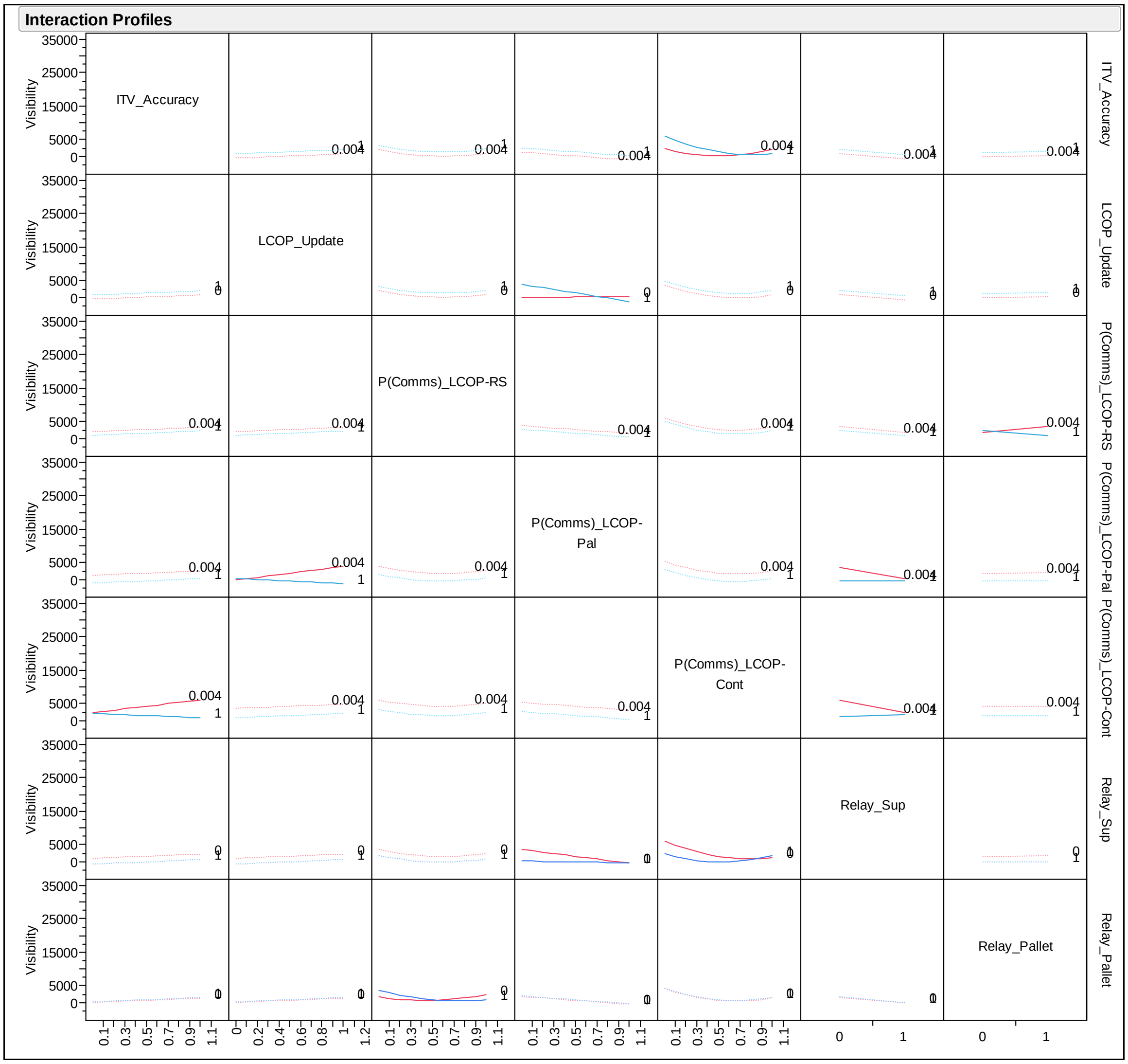


Figure 43. Interaction Profile Plot for Mean Difference in Area of Visibility, Hierarchical-Star Network Structure

Figure 44 shows the plot for the variability of the mean difference in area of visibility for the 257 design points categorized by traffic intensity. These results are analogous to the Star network structure. Under this network topology, enhanced network-enabled capabilities provided greater visibility, improving cargo operations and velocity management.

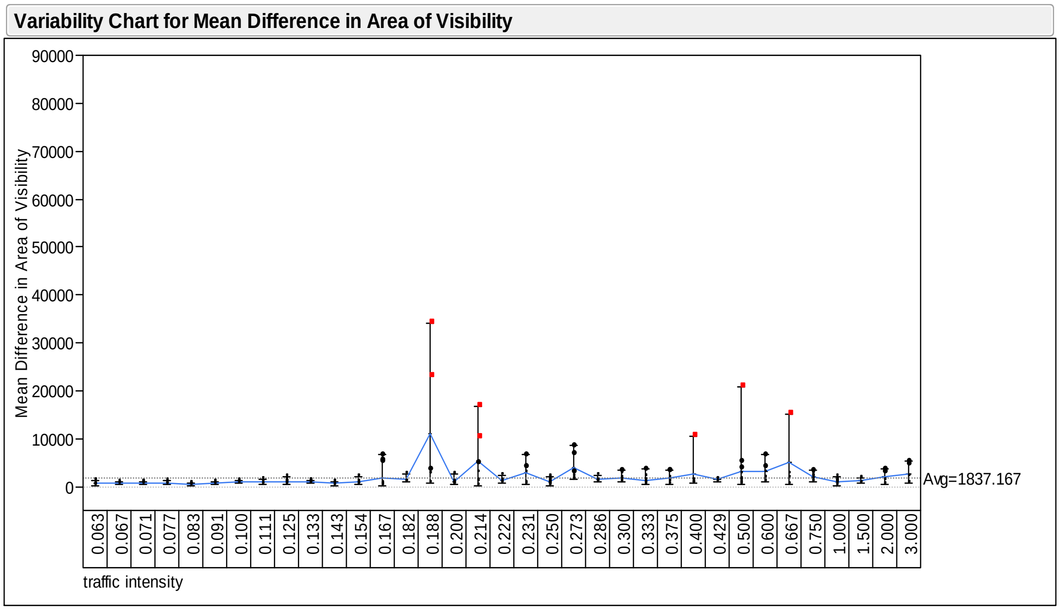


Figure 44. Interaction Profile Plot for Mean Difference in Area of Visibility, Hierarchical-Star Network Structure

10. Comparison and Simulation Insights

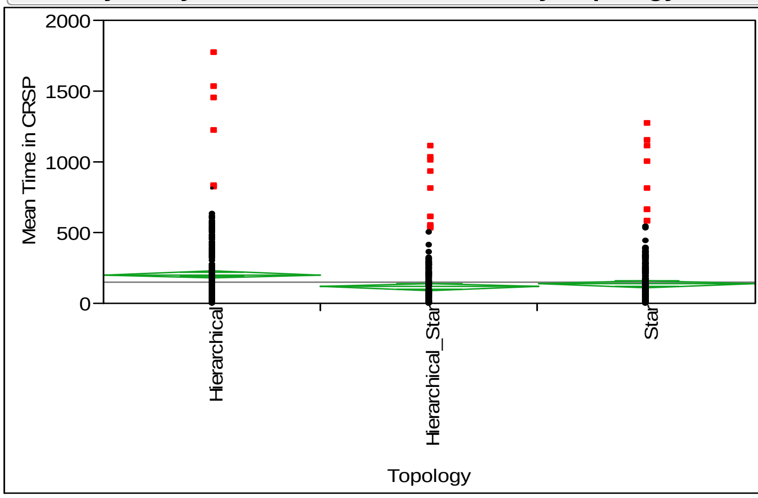
The findings during this analysis helped identify the impact of network-enabled capability on three measures of effectiveness: velocity, reliability, and visibility. Since this research focuses on the operations within the CRSP, the standards for these types of operations are not clearly defined in the JL (D) JIC, and performance data for operations within a CRSP is not readily available, the following assessment should be verified and validated by other parallel means.

a. Velocity and Reliability

Velocity is the speed at which convoys are processed in the CRSP, decreasing the mean time in CRSP increases velocity. Reliability is the degree of assurance and accuracy that CRSP operations will consistently meet capacity demands. Figure 46 shows summary statistics for the mean time in CRSP and the variability plot for all three network structures. Evidently, the network-enabled capability of the Star and Hierarchical-Star definitely provide an enormous benefit, when compared to the Hierarchical network structure. Simulation results indicate that the mean time in CRSP improved by 32% and 42% for the Star and Hierarchical-Star network structure, respectively, and this is a statistically significant improvement (p-value < 0.001).

Better velocity is achieved for the Star and Hierarchical-Star structures. Note in the plot the data points depicted in red are those resulting from traffic intensity greater than one. The vertical bars on the plot show that there is less volatility in the system for the Star and Hierarchical-Star network structures. Thus in addition to having better average velocity, these are also more reliable than the Hierarchical network structure.

Oneway Analysis of Mean Time in CRSP By Topology



Oneway Anova

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Topology	2	1009311	504656	11.4959	<.0001*
Error	768	33714168	43899		
C. Total	770	34723480			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Hierarchical	257	204.059	13.070	178.40	229.71
Hierarchical_Star	257	119.321	13.070	93.66	144.98
Star	257	139.206	13.070	113.55	164.86

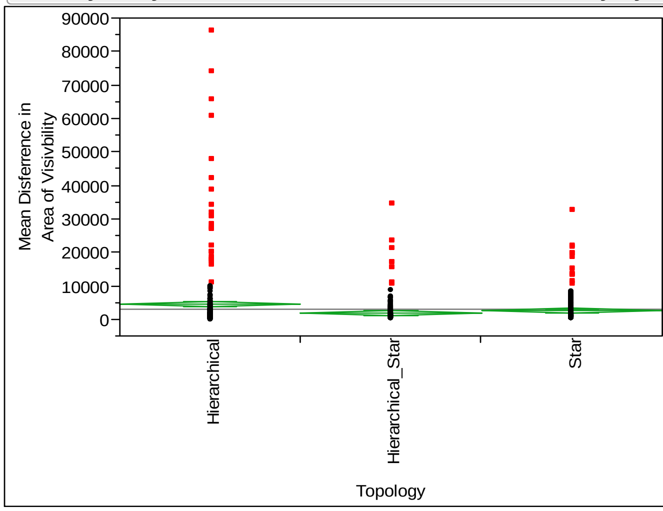
Std Error uses a pooled estimate of error variance

Figure 45. Summary Statistics and Comparison for Mean Time in CRSP (Best Viewed in Color)

b. Visibility

Figure 46 shows the summary statistics and variability plot for the mean difference in area of visibility for all three network structures. Simulation outcomes underscore the value of network-enabled capability provided by the Star and the Hierarchical-Star network structures. The mean difference in area of visibility improved by 43% and 59% for the Star and Hierarchical-Star network structure respectively, and this is a statistically significant improvement (p-value < 0.001). Thus better visibility is achieved by the Star and Hierarchical-Star networks than by the Hierarchical network.

Oneway Analysis of Mean Disferrence in Area of Visivbility By Topology



Oneway Anova

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Topology	2	992156292	496078146	10.1742	<.0001*
Error	768	3.7447e+10	48758492		
C. Total	770	3.8439e+10			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Hierarchical	257	4518.59	435.57	3663.5	5373.6
Hierarchical_Star	257	1837.17	435.57	982.1	2692.2
Star	257	2546.80	435.57	1691.7	3401.8

Std Error uses a pooled estimate of error variance

Figure 46. Summary Statistics and Variability Comparison for Mean Difference in Area of Visibility

D. CAPABILITY GAPS SIMULATION INSIGHTS

While these results are preliminary and are subject to further assessment in the CBA phase, there is enough fidelity to evaluate significant factors and to provide insights for the assessment of the current capabilities against required capabilities. Everything considered the Star and Hierarchical-Star network structures performed better than the Hierarchical network structure when comparing their impact against the ITV, cargo operations, and velocity management.

First, the results presented in this chapter demonstrate that velocity is affected by traffic intensity and ITV-Available, the most significant factors. The analysis highlights their impacts on the required capabilities, specifically, ITV, cargo operations and velocity management. On one hand, despite the benefits provided by the Star and Hierarchical-Star and the significant improvement in velocity, the simulation output suggests that, regardless of the network structure, there are several convoy configurations that the CRSP is incapable of handling on a sustained basis. Further analysis of the simulation traces is needed to assess the prevalence of this behavior. It is evident that CRSP lanes leverage ITV of the cargo, as the mean time in CRSP is mitigated with timely and accessible information, thus increasing velocity. On the other hand, there is an undeniable impact on velocity and reliability that underscores the added value provided by the Star and Hierarchical-Star network capabilities. For instance, with traffic intensity greater than near 1.0, the Hierarchical network structure case required a threshold of 0.723 of ITV-Available, compared to the Hierarchical-Star that required 0.539. Moreover, the results indicate the benefits of network-enabled capabilities provided by the Hierarchical-Star network structure. Two additional significant factors (probability of communications and communications relay capability) improve the mean time in CRSP, thus increasing velocity and reliability.

Second, the simulation output indicates that the Hierarchical network structure has limited capability; specifically, in the ability to share situational understanding, and the ability to access/share/exchange data information. The results presented on this chapter demonstrate that the mean difference in area of visibility is mainly influenced by the network-enabled capability at the operations center (supervisor lane), specifically, the LCOP-Sup probability of communications and the supervisor's communications relay capability. This has a direct impact on the ability of the other CRSP lanes to spread and access timely and accurate information to enhance situational understanding and awareness via the LCOP. Similarly, the simulation results indicate that those capability limitations are mitigated by the Star or the Hierarchical-Star network structures indicated by their significant factors such as the probability of communications between the pallet, container, and rolling stock lanes as well as the supervisor, pallet and container lane communication relay capability. These significant factors suggest that both of these network structures create the conditions that improve the level of visibility possessed by each of the element in the network.

To sum up the foregoing, the Hierarchical network structure displayed limited ability to share situational understanding and limited ability to access/share/exchange data/information, even with network-enabled capabilities provided.

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VI. CONCLUSIONS

A. SUMMARY

This research explores an operational scenario, implemented in the Logistics Battle Command (LBC) model, of transportation terminal node operations within a sustainment base supporting a Joint Force. Of particular interest is the evaluation of three network topologies; these are the Hierarchical, Star, and Hierarchical-Star network structures. There are 16 selected input factors for the Hierarchical and Star topologies, and 19 input factors for the Hierarchical-Star. Although these are large numbers of factors, an experiment could be conducted in a relatively short time by using the efficient NOLH design of experiments in conjunction with high performance computing clusters.

The input factors are derived from defined attributes in joint concepts and subject matter knowledge obtained during focused interviews. Similarly, the MOEs (velocity, reliability, and visibility) are derived directly from attributes defined in joint concepts. An exploratory data analysis of the simulation output provides insights into the strengths and weaknesses of the different network structures as well as the behavior of the LBC model. The primary findings and insights derived from the analysis are summarized below with disclaimer that, as with every model, the results are dependent on the input, the scope, and the assumptions.

- Velocity is affected by traffic intensity and ITV-Available, the most significant factors for all of the three network structures. Velocity improves as traffic intensity decreases. Setting ITV-Available to its highest value always results in better velocity.
- Overall, velocity improves by 32% and 42% with the Star and Hierarchical-Star network structures, respectively, in comparison to the Hierarchical network structure.
- Reliability is affected by traffic intensity and ITV-Available. Reliability improves with the Star and Hierarchical-Star network structures.
- The most significant factors influencing visibility differ by the network topology.
    - For the Hierarchical network structure, these are the communication relay capability at the supervisor lane, and the probability of communications between the supervisor and the LCOP.

    - For the Star network structure, these are the probability of communications between the LCOP and the pallet lane, as well as the LCOP and container lane, and the communications relay capability at the pallet lane.
    - For the Hierarchical-Star network structure, these are the communications relay capability at the supervisor lane, the probability of communications between the LCOP and the container lane, as well as the LCOP and pallet lane.
- Overall, visibility improves by 43% and 59% for the Star and Hierarchical-Star network structure, respectively, in comparison to the Hierarchical network structure.
- The Hierarchical network structure displays limited ability to share situational understanding, and in the ability to access/share/exchange data information.
- The Star and the Hierarchical-Star network structures improve the level of visibility possessed by each of the element in the network.

B. SIGNIFICANT CONTRIBUTIONS

Although architectural analysis based on subject matter expert input is the basis of the CBA process, and modeling and simulation is rarely used, the results from this research suggest that modeling and simulation combined with an efficient design of experiments will result in a more robust process and add credibility to the CBA findings. It is evident, that using the LBC model in a data-farming environment, along with very efficient NOLH experimental designs, can play a vital role in supporting more detailed second-order assessments. These, in turn, enable analysts to answer questions relating to the relative benefits of adding specific net-enabled capabilities. This study shows that some capabilities improve more than one MOE across two or more network structures, while others impact only one MOE for a specific network structure.

C. FUTURE RESEARCH

This effort explores the use of the LBC model and shows that it can be used in a data-farming environment to answer the research questions of interest. As a by-product of this effort, several modifications and enhancements made to the way the model gets input and prints output will make it easier to conduct similar studies in the future. The following are follow-on research possibilities and research questions that warrant further investigation.

First, traces of the simulation output exposed interesting and unusual behavior during the warm-up period. This study should be expanded to provide a more complete analysis of the warm-up and transient behavior of the scenario simulation, to make sure that the unusual behavior is not an undesirable result of some underlying modeling assumptions, and to better be able to recognize situations where the CRSP has difficulty handling the incoming cargo.

Second, using LBC to explore a theater level scenario would be beneficial. A similar approach would allow the analyst to investigate broader distribution operations, and the impact of network-enabled capabilities on these operations, to expose and assess issues in need of attention.

Third, other experiments may be necessary. Additional MOEs might be deemed important. Field data might suggest more realistic values for factor low and high levels. Other input factors related to either the net-centric structure or the operational scenario might be of interest. In all cases, an expanded experimental design would allow further analysis of network-enabled capabilities and attributes.

Finally, the full benefits of increased visibility under network-enabled operations are not likely to be realized unless they can lead to real-time redistributions of resources. Developing an LBC model that incorporates this capability would allow analysts to explore potential materiel solutions, and gain insight into how to the ability to interactively conduct distribution planning, execution, and in-transit redistribution based on a network-enabled LCOP might further improve the logistics distribution system.

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APPENDIX. PAIRWISE SCATTERPLOTS OF DESIGN POINTS

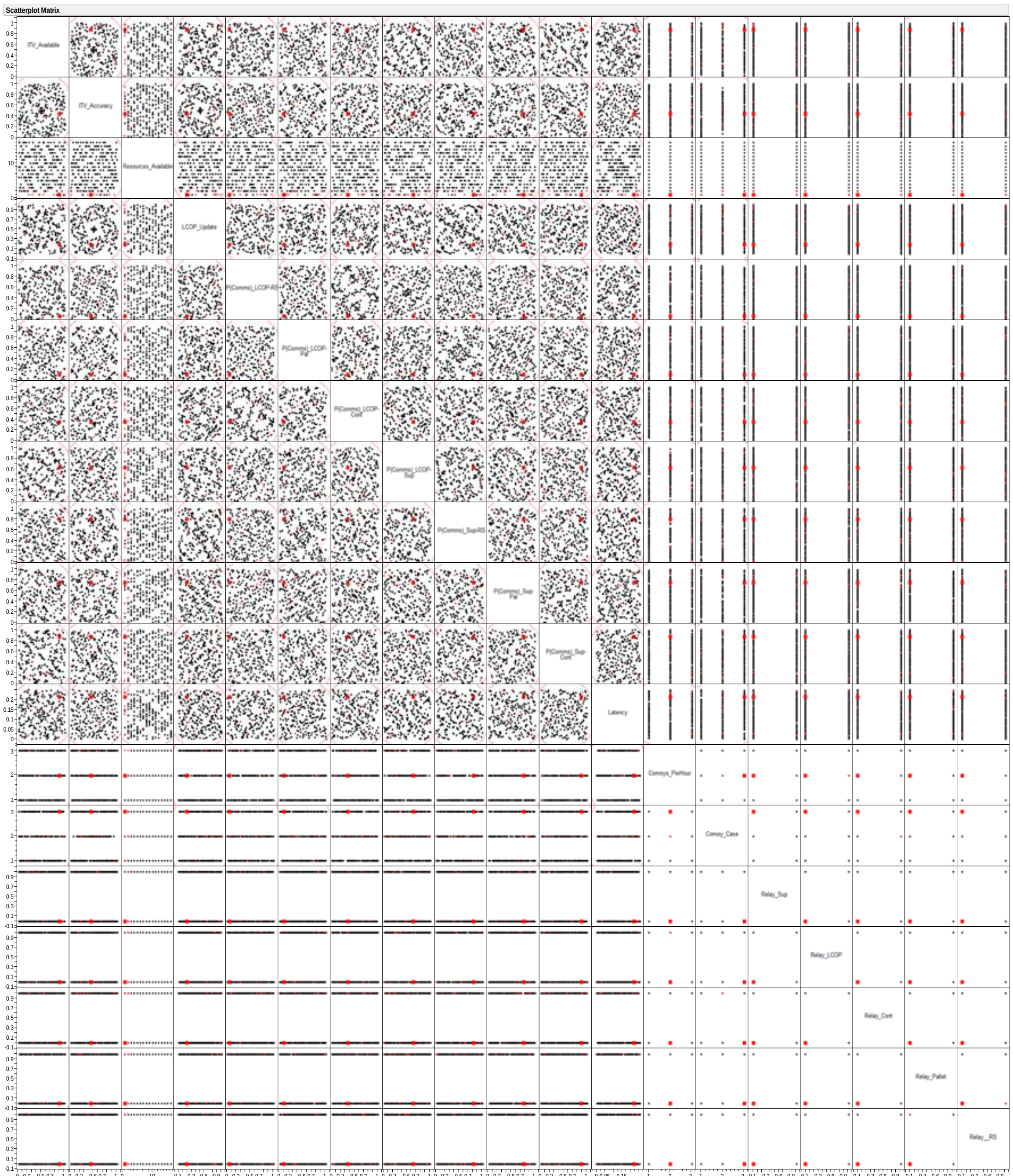

Figure 47. Hierarchical-Star Network Structure Pairwise Scatterplot of 257 Design Points Using NOLH Design

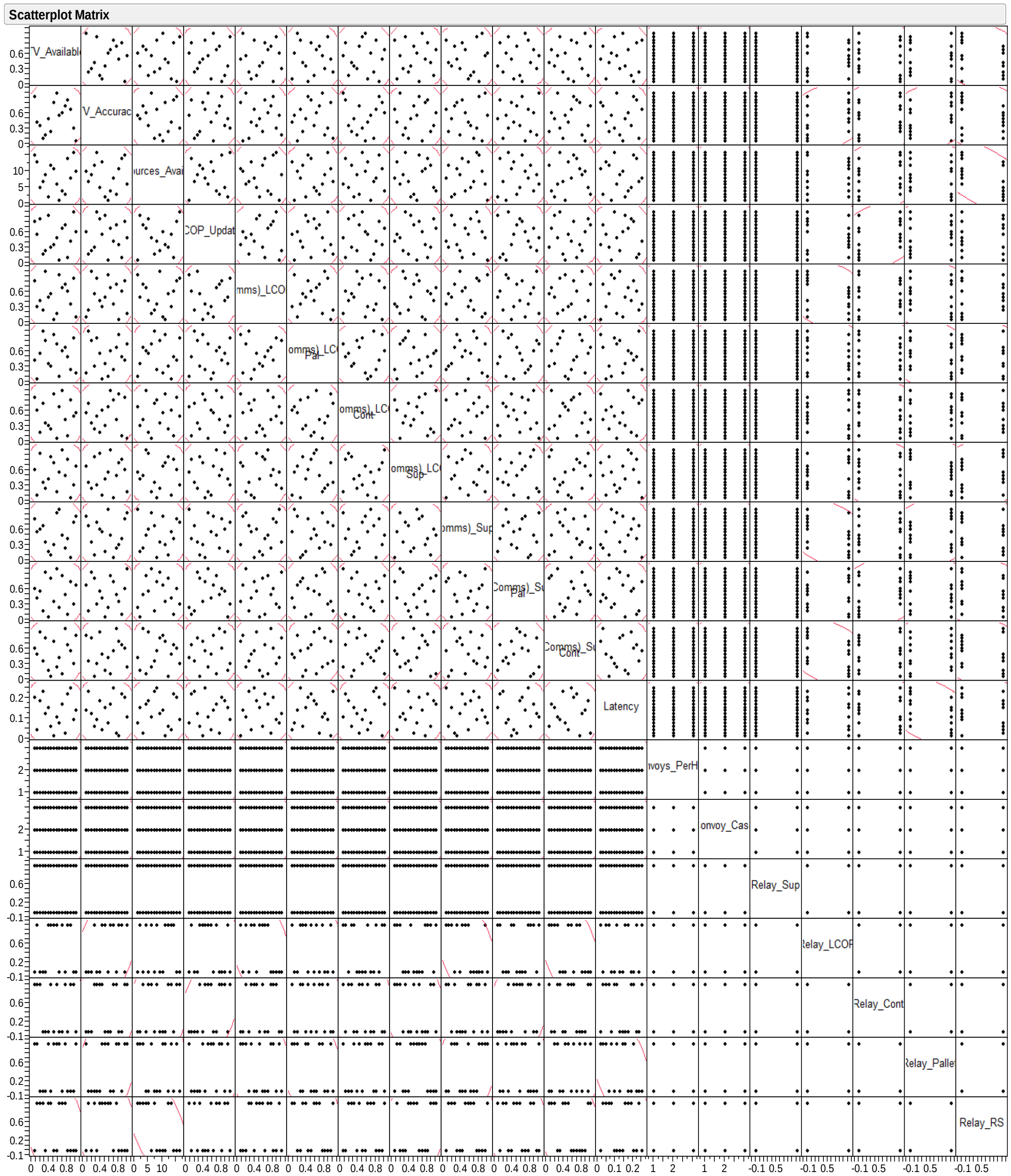

Figure 48. Hierarchical-Star Network Structure Pairwise Scatterplot of 96 Design Points Using COL Alejandro Hernandez Design

LIST OF REFERENCES

Buss, A. (2001). Discrete Event Programming with Simkit. *Simulation News Europe* 32/33: 15-25.

Center for Army Lessons Learned (2007). *Centralized Receiving and Shipping Point Handbook No. 07-33.*

Chairman of the Joint Chief of Staff (2007). *Instruction 3170.01F, Joint Capabilities Integration and Development System*. Retrieved November 10, 2007, from http://www.dtic.mil/cjcs_directives/cdata/unlimit/3170_01.pdf.

Chairman of the Joint Chief of Staff (2007). *Manual 3170.01C, Operation of the Joint Capabilities Integration and Development System.* Retrieved November 10, 2007, from http://www.dtic.mil/cjcs_directives/cdata/unlimit/m317001.pdf.

Cioppa, T. M. (2002). *Efficient Nearly Orthogonal and Space-Filling Experimental Design for High-Dimensional Complex Models*. Doctoral Dissertation, Naval Postgraduate School, Monterey, CA.

Cioppa, T. M. and Lucas, T. W. (2007). Efficient Nearly Orthogonal and Space-Filling Latin Hypercubes. *Technometrics* 49(1): 45-55.

Department of Defense (2003). *Focused Logistics Joint Functional Concept,* Version 1.0. Retrieved December 2, 2007, from http://www.dtic.mil/futurejointwarfare/jfc.htm.

Department of Defense (2005). *Net-Centric Environment Joint Functional Concept,* Version 1.0. Retrieved December 2, 2007, from http://www.dtic.mil/futurejointwarfare/jfc.htm.

Gaudard, M., Ramsey, P., and Stephens M. (2006). *Interactive Data Mining and Design of Experiments: the JMP® Partition and Custom Design Platforms*. Retrieved March 26, 2008, from http://www.jmp.com/software/whitepapers/.

Joint Chief of Staff (2005). *Net-Centric Environment Joint Integrating Concept*, Version 1.0. Retrieved December 2, 2008, from http://www.dtic.mil/futurejointwarfare/concepts/netcentric_jic.pdf,

Joint Chief of Staff (2006). *Joint Capabilities Document for Net-Centric Operational Environment,* Version 1.0. Retrieved December 2, 2007, from http://www.dtic.mil/futurejointwarfare/jfc.htm.

Joint Chief of Staff (2006). *Joint Logistics (Distribution) Joint Integrating Concept,* Version 1.0. Retrieved December 2, 2007, from http://www.dtic.mil/futurejointwarfare/concepts/jld_jic.pdf, Joint Chief of Staff/J-8 (2006). *Capabilities-Based Assessment User's Guide*, Version 2.0. Retrieved November 20, 2008, from http://www.dtic.mil/futurejointwarfare/strategic/cba_guidev2.pdf,

Joint Chiefs of Staff (2000). *Joint Publication 4-0, Doctrine for Logistics Support of Joint Operations*. Retrieved February 1, 2008, from http://www.dtic.mil/doctrine/jel/new_pubs/jp4_0.pdf.

Joint Chiefs of Staff (2000). *Joint Publication 4-01.4, Joint Tactics, Techniques, and Procedures for Joint Theater Distribution*. Retrieved February 1, 2008, from http://www.dtic.mil/doctrine/jel/new_pubs/jp4_01_4.pdf.

Joint Chiefs of Staff (2006). *Joint Publication 3-0, Joint Operations*. Retrieved March 26, 2008, from http://www.dtic.mil/doctrine/jel/new_pubs/jp3_0.pdf,

Kleijnen, J. P. C., Sanchez, S. M., Lucas, T. W., and Cioppa, T. M. (2005). State-of-the-Art Review : A User's Guide to the Brave New World of Designing Simulation Experiments. *INFORMS Journal on Computing,* Summer 2005, 17(3), 263-289.

Lajoie, B. S. (2007). Operating a Central Receiving and Shipping Point. *Army Logistician*, May-June 2007, 39(3), 24-28. Retrieved February 25, 2008, from http://www.almc.army.mil/alog/Back.html.

Melendez, M. D. (2007). Using Central Receiving and Shipping Points to Manage Transportation. *Army Logistician*, November-December 2007, 39(6), 3-5. Retrieved April 4, 2008, from http://www.almc.army.mil/alog/Back.html.

Montgomery, D. C., Peck, E.A., and Vining, G. G. (2006). *Introduction to Linear Regression Analysis* (4th ed.). New York: John Wiley & Sons, Inc.

Sall, J., Creighton L., and Lehman, A. (2007). *JMP® Start Statistics* (4th ed.). North Carolina: SAS Institute Inc.

Sanchez, S. M. (2000). Robust Design: Seeking the Best of All Possible Worlds. *Proceedings of the 2000 Winter Simulation Conference,* 69-76

Sanchez, S. M. (2006). A Design of Experiments Approach to Readiness Risk Analysis. *Proceedings of the 2006 Winter Simulation Conference,* 1332-1339.

Sanchez, S. M. (2006). NOLHdesigns spreadsheet. Retrieved October 17, 2007, from http://harvest.nps.edudiana.cs.navy.mil./SeedLab/

Sanchez, S. M. (2006). Work Smarter, Not Harder: Guidelines for Designing Simulation Experiments. *Proceedings of the 2006 Winter Simulation Conference,* 47-57.

Spencer, M. A. (2003). *The Operational Necessity for Logistics Common Operating Picture* (Research paper, Naval War College, 2003). Retrieved April 16, 2008, from http://handle.dtic.mil/100.2/ADA425990.

U.S. Army (2003). *Field Manual 4-0, Combat Service Support*. Retrieved February 12, 2008, from http://www.army.mil/usapa/doctrine/Active_FM.html.

U.S. Army (2003). *Field Manual 4-01.30, Movement Control.* (pp. 1-1). Retrieved February 12, 2008, from http://www.army.mil/usapa/doctrine/Active_FM.html.

U.S. Army (2007). *The United States Concept Capability Plan for Distribution Operations for the Future Modular Force 2015-2024*, Version 1.0. Retrieved March 25, 2008, from http://www.tradoc.army.mil/tpubs/pamndx.htm.

U.S. Army Combined Army Support Command (CASCOM) (2003). *Army Transportation Corps Functional Area Analysis*. Retrieved February 19, 2008, from http://www.tradoc.army.mil/tpubs/pamndx.htm.

U.S. Army Combined Army Support Command (CASCOM) (2006). *Digital Command and Control/Logistics Common Operating Picture Training Support Package.* Retrieved April 27, 2008, from http://www.cascom.lee.army.mil/td/td_multi/multifunindex.htm.

U.S. Army Training and Doctrine Command (TRADOC) (2006). TRADOC Pamphlet 525-66, *Military Operations Force Operating Capabilities*. Retrieved March 25, 2008, from http://www.tradoc.army.mil/tpubs/pamndx.htm.

U.S. Army Training and Doctrine Command (TRADOC), Army Capabilities Integration Center (2008). *Capabilities Based Assessment (CBA) Guide*.

U.S. Army Training and Doctrine Command Analysis Center (TRAC) Monterey, CA. (2008). *Individual Soldier Wireless Tactical Networking Functional Area Analysis*.

U.S. Army Training and Doctrine Command Analysis Center (TRAC), Fort Leavenworth, KS. (2005). *Joint Capabilities Integration and Development System (JCIDS) Analysis Code of Best Practice (COBP).*

U.S. Army Training and Doctrine Command Analysis Center (TRAC), Fort Leavenworth, KS. (2006). Constraints, *Limitations, and Assumptions Guide.*

U.S. Army Training and Doctrine Command Analysis Center (TRAC), Monterey, CA. (2007). *Individual Soldier Wireless Tactical Networking Study*. Program Coordination Sheet.

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